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DOUGLAS-FIR FERTILIZATION DECISION-MAKING FOR INDUSTRIAL USE: AN ESTABLISHMENT REPORT

BY
R. CARTER AND K. KLINKA*

*Faculty of Forestry
The University of British Columbia
2357 Main Mall
Vancouver, B.C.
V6T 1W5

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Pacific & Yukon Region
506 W. Burnside Road
Victoria, B.C. V8Z 1M5
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» PRINCIPAL RESEARCHERS

R.E. Carter and K. Klinka. Faculty of Forestry University of British Columbia Vancouver, B.C. January 1988

» ABSTRACT

Methodology and establishment of a research project, initiated in 1985, to study the effects of site-specific fertilization on immature coastal Douglas-fir ecosystems in southern British Columbia is described. Stand and site selection criteria, methods of ecosystem description, sampling, analysis and classification, selection of stands and treatments for fertilizer trials, and methods of evaluation of growth response are given in detail. By studying relationships between stand and site characteristics and growth response in 56 ecosystems, the project proposes to develop site-specific guidelines for coastal Douglas-fir fertilization decision-making for industrial use. This report provides a background reference for future publications reporting results of this project.

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» INTRODUCTION

Forest fertilization is one of the available practices used to increase forest productivity by adding to the existing nutrient supply of the soil. DeBell (1981) concluded that there are opportunities to increase forest productivity of some species on some sites in some situations; although he identified the uncertainty and site-specificity of growth response as major limitations. There is presently no information available for operational fertilization decision-making on a site-specific basis despite several large-scale Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] fertilizer trials established in the Pacific Northwest. Fertilizer response information is currently available only as a mean volume response by site class within fixed stand density regimes (Crown *et al.* 1977; Godfrey 1986).

Response to fertilization is a function of the extent to which nutrients are limiting growth and the ability of individual trees to respond to removal of this growth limitation before other limitations to growth begin to exert control. If response to fertilization is to be predictable, these other limitations and their interactions must be identified and examined.

The goal of this project is to develop site-specific guidelines for coastal Douglas-fir fertilization decision-making for industrial use. For each major site type in the very dry and dry maritime Coastal Western Hemlock biogeoclimatic subzones, these guidelines will propose the most responsive fertilizer treatment(s) (if such a treatment(s) was identified) and give an estimate of the three-year growth response (possibly five-year growth response, if the study is extended) for spaced immature Douglas-fir stands in southern coastal British Columbia.

Establishment activities have involved two steps. In the first step a survey was carried out to select, locate and describe suitable ecosystems using the specified site and stand selection criteria. Ecosystems located and described in this survey (candidate stands) were then analyzed according to their understory vegetation, climatic, and site characteristics, site indices, and foliar nutrient levels. This analysis was done to facilitate selection of stands for fertilizer trials (fertilized stands), which were to represent a wide range of site characteristics typical of immature stands of coastal Douglas-fir.

In the second step, potential nutrient deficiencies were diagnosed, fertilizer treatments prescribed, and fertilizer trials established in those stands selected on the basis of analyses conducted in the first step (fertilized stands or installations). More intensive stand and site data were collected during this step.

» APPROACH

To make silvicultural decisions that have a desirable effect on forest productivity, a forester should know the quality of different sites and ecosystems under management. This knowledge can then be used to select specific strategies and treatments that will sustain or enhance forest productivity. To accomplish the goal of this project the ecological framework provided by the biogeoclimatic ecosystem classification (BEC) system and an experimental design based on small fixed-area plots were adopted.

A forest ecosystem (biogeocoenose) is a segment of landscape relatively uniform in climate, soil, plants, animals, and microorganisms (Sukachev and Dylis 1964). Together, climate and soil (including topography) represent the environment or site of each ecosystem. Since vegetation and site characteristics are the most easily studied ecosystem components; forest ecosystems are commonly classified on this basis. Both approaches have difficulties — the use of vegetation presupposes knowledge of plant ecology, while selection of proper attributes for evaluating the integrated effects of site characteristics on plants also presents problems.

These difficulties have a common origin — different combinations of individual site factors may have the same effect on plants because of compensating effects. Therefore, site factors that directly affect plants are likely to be the most useful for description of vegetation-site relationships over a wide area. These numerous site factors can be simplified into light, heat, soil moisture, and soil nutrients (e.g., Cajander 1926; Pogrebnyak 1930;

Hills 1952; Rowe 1956; Major 1963; Bakuzis 1969; Krajina 1969). Thus, it is useful to define site quality on the basis of climate (light and heat), soil moisture, and soil nutrient variables as this approach helps us to better understand plant-site relationships (Klinka *et al.* 1984). Sites with the same combination of climate, soil moisture, and soil nutrient characteristics — so-called biologically-equivalent sites (Cajander 1926) — have the same site quality and similar vegetation and productivity potentials.

The easiest way to infer site quality is from vegetation of mature, old-growth, or climax ecosystems or, in their absence, through the evaluation of indicator plants and/or selected topographic and soil properties — the approaches inherent in the BEC system (Krajina 1969, 1972; Pojar *et al.* 1987). This classification system features site classification which organizes ecosystems according to their similarities in site characteristics. Site units are groups of ecosystems that have the same or equivalent environmental properties, vegetation and productivity potentials regardless of present vegetation. Site units will provide the framework that will be used to interpret and apply the results of fertilizer trials.

The adopted experimental design represents a compromise between short-term screening trials (e.g., Weetman and Fournier 1982, 1984) and large, more intensively studied trials such as the B.C. Forest Service Productivity Committee Installations (Godfrey 1986) and the Shawnigan Lake Trials (Crown *et al.* 1977). This compromise has necessitated a reduction in the number of stands that might have been studied using standard screening trial methods as a result of the time and costs associated with collection of ecosystem data necessary for determining site-specific growth response relationships. It also results in a less accurate estimation of area-based volume growth response than might be obtained through the use of larger installations with more replication. However, response will be evaluated in a large number of stands (56) and experience in several large trials suggests that response to fertilization varies considerably both within and among stands (Miller and Webster 1979); Miller *et al.* 1985). This suggests that obtaining highly accurate growth response estimates may be of less value when the results are extrapolated to other stands. The proposed methodology should provide most of the benefits of these alternative approaches.

» SITE AND STAND SELECTION CRITERIA

A total of 104 candidate stands were located throughout the study area with the assistance of government and industrial foresters. To simplify establishment of fertilizer trials and interpretations of growth response-site relationships several criteria were imposed on site and stand selection. Sites were selected to represent a wide range of environments supporting the growth of coastal Douglas-fir. Each site had to be relatively uniform in slope position, aspect, shape, and gradient; and had soils similar in the kind and arrangements of horizons, rooting depth, content of coarse fragments, mineralogy, and parent materials. Candidate sites were only considered to be suitable for selection if no recognizable changes in understory vegetation floristic composition, structure, and vigour existed and constituent plant species were relatively evenly distributed.

Stands selected for the project were required to have the following characteristics: (1) stand basal area or percent crown cover of Douglas-fir greater than or equal to 80% of all trees in the stand (2) even-aged between the age of 20 to 50 years (total age); (3) uniformly stocked with between 400 and 900 stems/ha; (4) live crown of all trees greater than 30% of the stem with adequate room for crown expansion of each tree; (5) stand area of adequate size for establishment of fertilizer trials (approximate minimum of one hectare); (6) no apparent pathological symptoms; and (7) no history of fertilization.

Sites and stands meeting the above criteria were considered to represent ecosystem individuals (Orloci 1964).

» METHODS OF ECOSYSTEM ANALYSIS

» Site Description

Within a candidate stand (ecosystem individual) a representative sample plot of 20 x 20 m (0.04 ha) was subjectively located. Site description for each sample plot followed a simplified version of the standard procedure employed by the Ecological Programme Staff of the B.C. Ministry of Forests

and Lands (Walmsley *et al.* 1980). Sites were described in terms of biogeoclimatic unit, elevation, slope position, aspect, and gradient, and ground surface cover by forest floor, decaying wood, mineral soil, and coarse fragments/bedrock.

» Vegetation Description

Vegetation on each sample plot was analyzed employing the techniques of biogeoclimatic ecosystem classification. This analysis included the identification and listing of all vascular plants, bryophytes, and lichens present on the plot. Visual estimates of species cover, using a species significance scale, were also made according to the recognized A (tree), B (shrub), C (herb), and D (moss) layers (Pojar *et al.* 1987). Species growing exclusively as epiphytes, on decaying wood, and on coarse fragments or rocks were not included in this list. The nomenclature followed, with few exceptions, Hitchcock *et al.* (1955-1969) for vascular plants; Crum *et al.* (1973) and Stotler and Crandall-Stotler (1977), and Ireland *et al.* (1980) for bryophytes; and Hale and Culberson (1970) for lichens.

» Stand Description

In each candidate stand, age, height, and diameter at breast height was measured in 2 dominant and 3 codominant trees; in each fertilized stand, a minimum of 30 dominant and codominant trees were measured. Site index was determined according to Bruce's site curves as presented in Mitchell and Cameron (1985). Stocking was assessed visually or taken from spacing or cruise data when available. Age at breast height, total tree height, diameter at breast height, length of the live crown (defined as height to the first whorl having 3 or more live branches), width of the live crown at the base of the live crown (assessed visually), and distance to the nearest neighbouring dominant or codominat tree in each of four 90° quandrants was measured for each fertilzed and control tree. Leaf area index will be determined for each of the fertilized stands during 1988.

» Soil Description, Sampling, and Analysis

Soil description in the survey phase was qualitative, and included thickness of forest floor, humus form type, soil particle size, coarse fragment content, root distribution, rooting depth, soil moisture regime, and soil nutrient regime. Humus forms were identified according to Klinka *et al.* (1981). Soil texture, coarse fragment content, and root distribution were described at depths of 0-30, 30-60, and 60-100 cm where applicable. Actual soil moisture regimes (SMRs) and actual soil nutrient regimes (SNRs) were identified using the field procedure described in Klinka *et al.* (1984). Notes were also made on the presence of gleying or flooding and the kind of A soil horizon, if present (Canada Soil Survey Committee 1978).

Intensive soil sampling was conducted in each fertilized stand. Forest floor and mineral soil physical and chemical properties were examined and sampled separately at 5 sampling points selected on a stratified random basis within each stand. Composite samples of forest floor and composite bulk samples of the mineral soil at a 0-30 cm depth were taken from three points of an equilateral triangle (2 m on a side), located over each point. Bulk density was measured near the point from which each soil sample was collected by cutting out a core, measuring its volume (by measuring the volume of water required to fill the resulting hole lined with a thin plastic sheet), and measuring its mass after oven-drying at 105° C to constant weight.

All soil samples were air-dried to constant weight in the laboratory. For chemical analysis, forest floor samples were ground in a Wiley mill to pass a 2-mm sieve, while mineral soil samples were passed through a 2-mm sieve to separate coarse fragments. Soil pH was measured with a pH meter using a 1:1 suspension in water for mineral soil and a 1:5 suspension for forest floor material. Total C was determined using a Leco Induction Furnace (Bremner and Tabatabai 1971). Total N was determined by semimicro-Kjeldahl digestion followed by colorimetric estimation of NH_4 using a Technicon Autoanalyzer (Anonymous 1976). Mineralizable-N was determined by an anaerobic incubation procedure modified from Waring and Bremner (1964). Released NH_4 was determined colorimetrically by use of a Technicon Autoanalyzer. Phosphorus was measured by the extraction procedure of Mehlich (1978). Total S analyses in the forest floor material were conducted using a Fisher Model 475 Sulphur Analyzer while available SO_4-S was determined by ammonium-acetate extraction (Bardsley and Lancaster 1965). Extracted sulphate was reduced to

sulphide by HI and the sulphide was then determined colorimetrically (Kowalenko and Lowe 1972). Extractable K, Mg, and Ca were determined by extraction with Morgan's solution of sodium acetate pH 4.8 (Greweling and Peech 1960). The extracted cations were then measured by atomic absorption spectrophotometry. Cation exchange capacity (CEC) and exchangeable K, Mg, Ca, and Na were determined by displacement with 1.0 N NH_4OAc. The displaced cations were analyzed by atomic absorption spectrophotometry (Price 1978).

Soil nutrient variables were expressed as concentrations on a dry mass basis and, where applicable, on a weight per unit area basis. The weight per unit area calculation used bulk density corrected for coarse fragment content for both forest floor and mineral soil and represents weight of nutrient per hectare in the forest floor and surface 30 cm of the mineral soil.

Actual SMRs of fertilized stands were quantitatively characterized using components of the annual water balance calculated for each site and classified as recommended by Klinka *et al.* (1984) into one of the following classes: extremely dry, very dry, moderately dry, slightly dry, fresh, moist, very moist, wet, or very wet (Table 1). Potential (E_{max}) and actual (E_t) transpiration were calculated using a slight modification of the Energy-Soil Limited (ESL) water balance model of Spittlehouse and Black (1981). This model is driven by solar radiation, temperature and precipitation using potential rooting depth and texture data to calculate available water storage capacity. The current model does not adjust for aspect or slope and used 30-year normals for temperature and precipitation (Canadian Climate Program 1982) rather than annual data; future studies will be based on annual data.

Actual SNRs of fertilized stands were quantitatively characterized and classified according to Kabzems and Klinka (1987) into one of the following classes: very poor, poor, medium, rich or very rich classes (Table 2).

Table 1. A tentative key to identification of soil moisture regimes in coastal British Columbia (a modified version of Klinka *et al.* 1984).

Rooting-zone groundwater absent during the growing season	
Water deficit occurs:	
Deficit >5 months or AET/PET <40%	excessively dry
Deficit >3.5 but <5 months, AET/PET <60 but >40%	very dry
Deficit >1.5 but <.5 months, AET/PET <90 but >60%	moderately dry
Deficit >0 but less <1.5 months, AET/PET >90%	slightly dry
No water deficit occurs:	
Utilization occurs	fresh
No utilization occurs (groundwater table >60 cm deep may be present)	moist
Rooting-zone groundwater present during the growing season	
Ground water table >60 cm deep	moist
Groundwater table >30 but <60 cm deep	very moist
Groundwater table >0 but <30 cm deep	wet
Groundwater table at or above the ground surface	very wet

Table 2. Means and standard deviations (brackets) of forest floor and mineral soil properties which are used to characterize the actual soil nutrient regimes in coastal British Columbia [after Courtin *et al.* (1987) and Kabzems and Klinka (1987)].

Property	Actual Soil Nutrient Regime				
	very poor	poor	medium	rich	very rich
Forest floor pH	3.8	4.0	4.1	4.5	5.0
	(0.25)	(0.47)	(0.62)	(0.43)	(0.43)
Forest floor C/N	73	42	34	20	21
	(7.4)	(7.3)	(6.8)	(4.5)	(4.5)
Mineralizable N	<10	18	54	113	242
(kg/ha)	ND	(7)	(20)	(39)	(130)
Sum of available Ca,	1386	873	1225	1743	5066
Mg, and K (kg/ha)	(1683)	(650)	(577)	(1088)	(1961)

Foliage Sampling and Analysis

Foliage was sampled during the dormant season (October to November) according to the procedures outlined in Ballard and Carter (1986). Fifteen dominant and codominant trees were sampled and their foliage combined to make a single composite sample. Samples were oven-dried at 70° C as soon as possible and weight per 100 needles was determined before grinding. Each sample was analyzed in duplicate for total N, P, K, Ca, Mg, S, SO_4-S, Cu, Zn, Mn, Fe, active-Fe, and B according to the methods outlined in Ballard and Carter (1986). The results of chemical analysis were expressed as concentrations (dry mass basis) and as milligrams nutrient element per 100 needles. Post-treatment foliar analysis in the fertilized stands was carried out on an individual tree basis following the same methods.

METHODS OF ECOSYSTEM CLASSIFICATION

Sample plots established in 104 candidate stands were classified at the regional and local levels of integration using the methods and system of biogeoclimatic ecosystem classification (BEC) as described by Klinka and Krajina (1987) and Pojar *et al.* (1987).

Allocation of sample plots into climatic strata was done by locating the plots on the map of Nuszdorfer *et al.* (1985) and identifying the biogeoclimatic units from the map symbol and legend. The identified units were renamed according to the results of a correlated classification for coastal British Columbia. (Ecological Programme Staff, B.C. Ministry of Forests and Lands).

The purpose of vegetation classification was to assist in stratification of the selected sites into floristically-inferred segments of the soil moisture and nutrient gradients. The classification was based on the plant species p esent in the understory stratum (shrub, herb, and moss layers), using tabular methods (Westhoff and van der Maarel 1980), diagnostic criteria proposed by Pojar *et al.* (1987), and a computerized tabling program (VTAB; Emanuel 1987). To improve consistency of groupings obtained from the tabular comparison, multivariate analysis of vegetation was conducted using principal components analysis (PCA; Fox and Guire 1976) and reciprocal averaging (RA; Gauch 1977). PCA was performed on a correlation matrix (Noy-Meir and Whittaker 1977).

The allocation of sample plots into site units, associations, series, and types distinguished for coastal British Columbia by the Ecological Programme

Staff of the B.C. Ministry of Forest and Lands was done according to the biogeoclimatic subzone or variant, soil moisture regime, soil nutrient regime, and diagnostic edaphic characteristic(s) (Klinka and Krajina 1987) identified for each plot.

Complementary to site classification, computer-assisted spectral analysis (Emanuel 1987; Klinka and Krajina 1987; Green *et al.* 1987) was employed to characterize vegetation units and to determine the usefulness of understory indicator plant species in inferring site quality. This analysis is based on calculating frequencies of indicator species groups (Klinka *et al.* 1988) for a given site attribute (e.g., climate, soil moisture, or soil nutrients) within a plot (or group of plots). Resulting frequencies (relative proportions of indicator species groups based on species cover) were used to produce spectral histograms and as variables for later analysis of growth response-site interactions.

» BIOGEOCLIMATIC ECOSYSTEM CLASSIFICATION

» Biogeoclimatic Units

The distribution of candidate stands (Figure 1) was confined to that portion of southern coastal British Columbia located within the Coastal Western Hemlock (CWH) biogeoclimatic zone (Krajina 1969). This area is characterized by a drier maritime cool mesothermal climate (Koppen *in* Trewartha 1968), montainous topography, and a nearly continuous evergreen forest cover.

Old-growth forests in the CWH zone are usually dominated by western hemlock [*Tsuga heterophylla* (Raf.) Sarg.] and Douglas-fir with significant amounts of western redcedar (*Thuja plicata* Donn *ex* D.Don *in* Lamb.). Second-growth forests are usually dominated by naturally regenerated or planted Douglas-fir. The characteristic floristic features of zonal ecosystems are a high cover of several ericaceous shrub species (e.g., *Gaultheria shallon, Menziesia ferruginea*, and *Vaccinium parvifolium*) and acidiphilous mosses (e.g., *Hylocomium splendens, Kindbergia oregana, Plagiothecium undulatum*, and *Rhytidiadelphus loreus*).

The study area is underlain by volcanic rocks (Vancouver Island) or granitic rocks (coastal mainland). Glacial till is the most common landform, but fluvial or marine deposits are frequently encountered. Soils are typically coarse-skeletal (loamy sands to sandy loams with high coarse fragment contents), acidic Humo-Ferric Podzols (Canada Soil Survey Committee 1978) with Mor humus forms (Klinka *et al.* 1981).

Candidate stands were distributed in four biogeoclimatic units, which correspond to vegetation-inferred variations of maritime cool mesothermal climate (Tables 3 and 4). The climatic data presented in Table 4 suggest that the main contrast occurs between the dry and wet CWH units. Climatically closely related dry CWH units appear to be separated by growing-season precipitation and mean precipitation of the driest summer month. The CWHxm subzone (formerly the CDFb subzone and CWHa1 variant), which now represents the driest portion of the CWH zone, is floristically akin to the adjacent (usually montane) CWHdm subzone (formerly the CWHa2 variant)— with the major floristic difference being in the cover of salal.

» Vegetation and Site Units

Six vegetation units were distiquished. Floristic affinities and relationships among these vegetation units are presented as a synopsis (Table 5), diagnosis (Table 6), and ordination (Figure 2). Environmental features selected to characterize the candidate sites within each unit are presented in Table 7.

The 29 species used as diagnostic species (Table 6) were also analyzed using PCA. The first two components accounted for 47% of the explained variance. The species with the strongest correlation with the first PCA axis were *Gaultheria shallon, Rubus spectabilis, Tiarella trifoliata, Athyrium felix-femina, Gymnocarpium dryopteris, Galium triflorum*, and *Mahonia nervosa*. Consideration of each units' characteristics (Table 7) suggests that these species increase or decrease in cover with increasing soil moisture and nutrients. The species with the strongest correlation with the second PCA axis were *Achlys triphylla, Mahonia nervosa, Rubus ursinus*, and *Rosa gymnocarpa*. The distribution of these units along the climatic gradient suggests that these species increase in cover with increasing temperature and as regional climate becomes increasingly drier (from wetter and

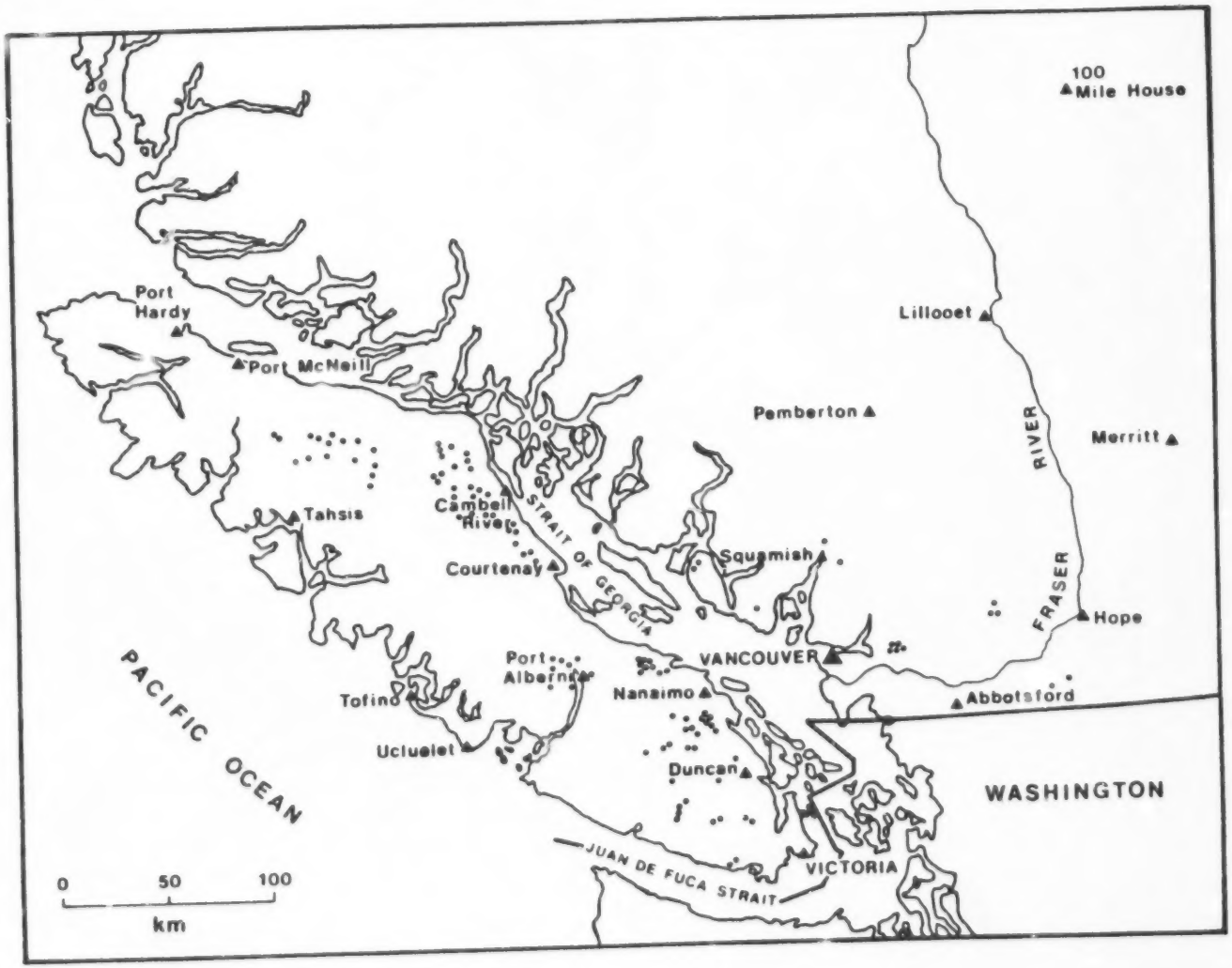

Figure 1. Distribution of sampled stands.

Table 3. Distribution of candidate stands in biogeoclimatic units.

Biogeoclimatic subzone of plots	Number
Very Dry Maritime CWH (CWHxm) [1]	84
Dry Maritime CWH (CWHdm)[2]	11
Very Wet Maritime CWH (CWHvm)[3]	9

[1] formerly composed of the CDFb subzone and CWHa1 variant
[2] formerly CWHa2 variant
[3] formerly CWHb subzone

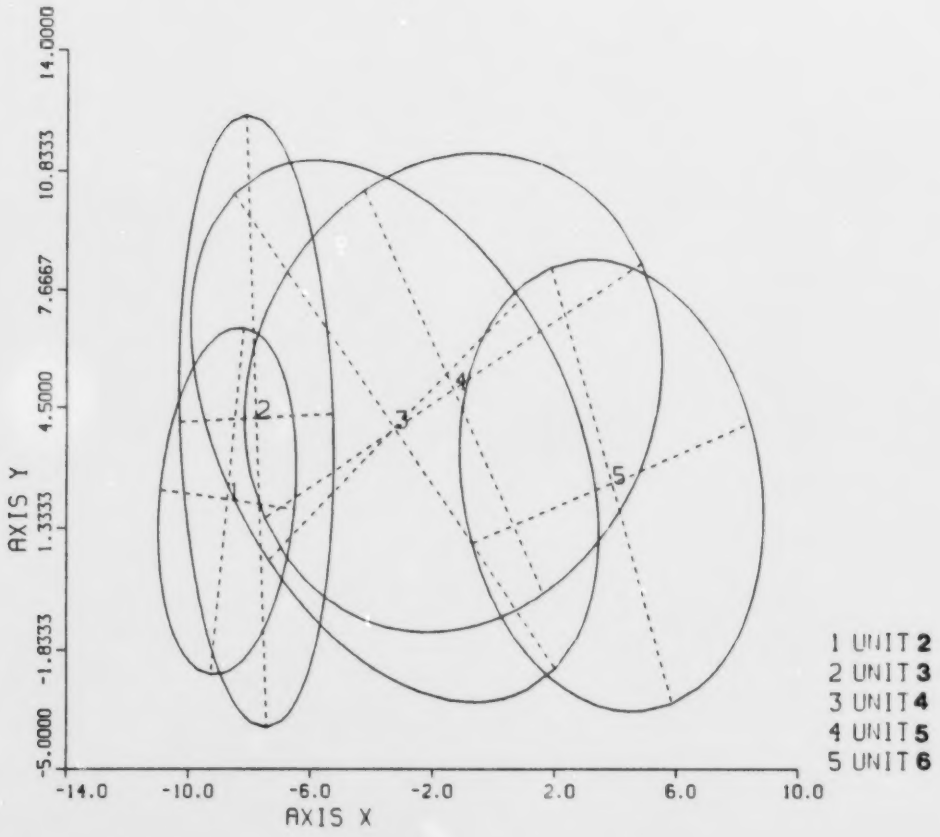

Figure 2. 95% confidence elipses for the ordination of the 104 study plots in their vegetation units.

Table 4. Means, standard deviations, and ranges of selected climatic parameters for biogeoclimatic units present in the study area. The source of climatic data is Environment Canada (1982).

Climatic parameter	Biogeoclimatic unit			
	CWHxm1	CWHxm2	CWHdm	CWHvm
Number of stations for precipitation data	69	12	53	34
Mean annual precipitation (mm)	1425	1969	1827	2787
	326	387	326	680
	857-2176	1381-2721	1221-2412	1555-4387
Mean precipitation April-Sept. (mm)	346	462	498	752
	79	128	89	200
	206-533	297-706	325-675	447-1465
Mean precipitation of the driest month (mm)	37	49	53	85
	10	20	10	29
	17-59	24-88	34-78	56-130
Mean precipitation of the wettest month (mm)	238	322	292	436
	63	63	55	103
	137-392	214-438	197-450	234-625
Number of stations for temperature data	46	8	23	21
Mean annual temperature (C)	9.4	8.8	9.8	8.2
	0.5	0.7	0.4	1.1
	8.2-10.7	7.8-10.0	8.7-10.3	6.3-10.1
Mean temperature of the coldest month (oC)	1.8	1.4	1.9	0.3
	0.8	1.5	0.7	2.7
	0.2-3.4	-0.5-3.9	0.5-3.4	-4.5-3.7
Mean temperature of the warmest month (C)	17.1	16.5	17.6	16.0
	0.7	0.7	0.5	1.1
	15.1-18.7	14.8-18.3	16.6-18.5	13.8-18.8
Number of months with mean temperature >10 C	5.4	5.2	5.7	4.8
	0.5	0.5	0.4	0.6
	5-6	5-6	5-6	4-6
Index of continentality[1]	13.8	13.1	15	14
	2.5	4.5	1.5	6.1
	6-18	4-17	11-18	4-23

[1] After Rose and Grant (1976).

cooler in the CWHdm to the drier and warmer CWHxm subzone).

Only the first component showed significant differences among vegetation units using ANOVA. Along the first component 75% of the among-plot variance was due to differences between the delineated vegetation units.

The floristic differentiation of the units was relatively weak due to the depauperated understory vegetation (*c f.* Mueller-Dombois 1959). This is indicated by a relatively large group of species common to all ecosystems sampled and a small number of species included in diagnostic cominations of species (Table 6). However, the results demonstrate that the selected ecosystems cover a wide segment of the soil moisture and nutrient gradients in the dry-CWH units supporting the growth of Douglas-fir (Table 7). The range of site indices and actual SMRs and SNRs in the candidate stands (Table 8) in relation to the vegetation units (Table 7) demonstrates the nearly complete coverage of the productivity gradient.

Regardless of the presence of early-seral vegetation, it was possible to delineate five units that approximate site associations; the Gaultheria-Mahonia-Rhytidiadelphus and Mahonia-Kindbergia vegetation units are considered to be ecologically equivalent, i.e., they form a single site association. The Vaccinium-Gaultheria plant association corresponds to the Vaccinium-Gaultheria site association which represents moderately to slightly dry and nutrient-very poor to nutrient-poor sites in the Montane CWHvm2 variant (Klinka and Krajina 1986). Relationships of dry-CWH vegetation units to the actual SMRs and SNRs of their sites is shown on the edatopic grid (Figure 3). Superimposed on the grid are tentative site associations that have been distinguished in the CWHdm subzone throught the work of the Ministry of Forests and Lands correlation program. All sample plots of any CWHdm-vegetation unit that were confined to the area of a single site association were allocated to that site association. In consequence, five site associations Gaultheria-Lichen, Gaultheria-Kindbergia, Rhytidiadelphus-Plagiothecium, Polystichum-Trillium, and Tiarella-Athyrium were identified.

This approach to site classification helps separate the effects of historical disturbances and/or treatments from site factors on vegetation (Klinka *et al.* 1985; Pojar *et al.* 1987). For example, the contrast in salal cover between the Gaultheria-Mahonia-Rhytididadelphus and Mahonia-Kindbergia (Table 6)

Table 5. Synopsis of distinguished seral Douglas-fir vegetation units.

Plant association Plant subassociation
$Vaccinium alaskaense-Gaultheria shallon
$Gaultheria shallon-Mahonia nervosa
$Gaultheria shallon-Mahonia nervosa-Polytrichum juniperinum
$Gaultheria shallon-Mahonia nervosa-Rhytidiadelphus loreus
$Mahonia nervosa-Kindbergia oregana
$Polystichum munitum-Mycelis muralis
$Polystichum munitum-Mycelis muralis-Mahonia nervosa
$Polystichum munitum-Mycelis muralis-Rubus spectabilis

The symbol $ denotes a seral vegetation unit.

Table 7. Synopsis of selected characteristics for distinguished vegetation units.

Vegetation unit	1	2	3	4	5	6
	VG	GMP	GMR	MK	PMM	PMR
Number of plots	3	13	26	26	30	6
Biogeoclimatic unit[1]	CWHvm2	CWHxm-dm				
Elevation (m)	645	268	233	247	227	213
Slope gradient (%).	46	16	17	16	19	8
Actual SMR[2]	MD	VD	MD-SD	MD-F	SD-F	M
Actaul SNR[3]	P	VP-P	VP-M	VP-M	P-R	R-VR
Humus form[4]	MR	MR-MD	MR-MD	MR-MD	MR-MD	MD
Forest floor depth (cm)	11	3	4	3	4	4
Soil particle size[5]	L	S-L	S-L	S-L	S-L	L
Coarse fragments (%)	57	58	56	57	44	21
Rooting depth (cm)	78	58	62	57	69	92
Ground cover (%)						
- forest floor	55	75	82	69	70	82
- decaying wood	10	13	11	18	22	7
- mineral soil	2	3	<1	3	3	10
- coarse fragments	33	9	6	10	5	<1
Site index - mean	22.0	20.6	28.5	27.9	33.5	34.3
(m/50 yrs) - std. dev.	1.7	2.3	3.3	3.5	2.3	2.9

[1] CWHvm - Very Wet Maritime CWH subzone, CWHxm - Very Dry Maritime, CWH subzone, CWHdm - Dry Maritime CWH subzone.

[2] SMR (soil moisture regime); VD - very dry, MD - moderately dry, SD - slighlty dry, F - fresh, M - moist.

[3] SNR (soil nutrient regime); VP - very poor, P - poor, M - medium, R - rich, VR - very rich.

[4] MR - Mor, MD - Moder.

[5] L - loamy, S - Sandy.

Table 6. Diagnostic combinations of species for vegetation units distinguished for 104 candidate stands.

Plant association / Plant subassociation		VG		GM GMP		GM GMR		MK		PM PMM		PM PMR	
Column number		1		2		3		4		5		6	
Number of plots	Diagnostic	3		13		26		26		30		6	
Species	value	Presence class[1] and mean species significance[2]											
$Vaccinium alaskaense-Gaultheria shallon (VG) p.a.													
Abies amabilis	(d,c)[3]	5	2.5			I	+.0	I	+.5	I	+.0		
Cladina rangiferina	(d)	4	+.1	II	3.3	I	+.0	I	+.0				
Cornus canadensis	(d)	4	4.0	I	+.0	II	2.2	II	1.6	II	2.4	II	2.4
Epilobium angustifolium	(d)	4	1.0	II	+.0	II	+.0	I	1.6	I	+.1	II	1.1
Pogonatum alpinum	(d)	4	+.1			I	+.0	I	+.0				
Rhytidiopsis robusta	(d)	4	2.2	I	+.0	I	+.0	I	+.0	I	+.0	I	+.0
Salix sitchensis	(d)	4	1.4	II	+.1	I	+.3	II	+.0	I	+.0	I	+.0
Sorbus sitchensis	(d)	4	+.1										
Vaccinium alaskaense	(d,cd)	5	6.7			I	+.0	I	1.0	II	1.8	I	+.8
$Gaultheria shallon-Mahonia nervosa (GM) p.a.													
Gaultheria shallon	(dd)	4	6.2	V	9.1	V	8.5	V	5.0	IV	4.5	I	1.4
Rosa gymnocarpa	(d)			III	1.6	III	1.5	I	+.0	I	+.0		
$Gaulthera shallon-Mahonia nervosa-Polytrichum juniperinum (GMP) p.sa.													
Polytrichum juniperinum	(d)			III	1.0	I	+.0	I	+.0	I	+.0	I	+.0
$Gaultheria shallon-Mahonia nervosa-Rhytidiadelphus loreus (GMR) p.sa.													
Achlys triphylla	(d)			II	+.8	IV	4.3	IV	3.8	V	4.4	III	4.1
Rhytidiadelphus loreus	(d)	2	+.0	I	+.0	III	1.6	II	+.0	III	1.0	II	+.0
$Mahonia nervosa-Kindbergia oregana (MK) p.a.													
$Polystichum munitum-Mycelis muralis (PM) p.a.													
Galium triflorum	(d)			I	+.0	I	+.0	II	+.0	IV	1.9	V	2.6
$Polystichum munitum-Mycelis muralis-Mahonia nervosa (PMM) p.sa.													
Achlys triphylla	(d,c)			II	+.8	IV	4.3	IV	3.8	V	4.4	III	4.1
Gaultheria shallon	(d)	4	6.2	V	9.1	V	8.5	V	5.0	IV	4.5	I	1.4
Hylocomium splendens	(d)	2	+.0	III	1.3	III	2.6	IV	2.6	IV	4.1	II	+.6
Mahonia nervosa	(d)	2	+.6	V	3.1	V	3.2	IV	4.0	IV	3.0	I	1.4
Rubus ursinus	(d,c)	4	+.1	V	1.6	V	2.2	V	2.9	V	2.5	III	1.8
$Polystichum munitum-Mycelis muralis-Rubus spectabilis (PMR) p.sa													
Athyrium filix-femina	(d,c)	2	+.0			I	+.0	I	+.0	I	+.2	V	4.3
Bromus vulgaris	(d)			II	+.0	II	+.4	II	+.3	II	1.7	IV	2.3
Dicentra formosa	(d)											III	2.2
Gymnocarpium dryopteris	(d)							I	+.0	I	+.4	IV	4.1
Petasites palmatus	(d)											III	2.8
Rubus spectabilis	(d,cd)	2	2.1	I	+.0	I	+.5	III	2.5	III	3.0	V	6.4
Sambucus racemosa	(d)							I	+.0	I	+.0	IV	3.6

[1]Presence classes as percent of frequency: I = 1-20, II = 21-40, III = 41-60, IV = 61-80, V = 81-100.

[2]Species significance class midpoint percent cover and range: + = 0.2 (0.1 - 0.3), 1 = 0.7 (0.4 - 1.0), 2 = 1.6 (1.1 - 2.1), 3 = 3.6 (2.2 - 5.0), 4 = 7.5 (5.1 - 10.0), 5 = 15.0 (10.1 - 20.0), 6 = 26.5 (20.1 - 33.0), 7 = 41.5 (33.1 - 50.0), 8 = 60.0 (50.1 - 70.0), 9 = 85.0 (70.1 - 100).

[3]Species diagnostic values: d - differential, dd - dominant differential, cd - constant dominant, c - constant.

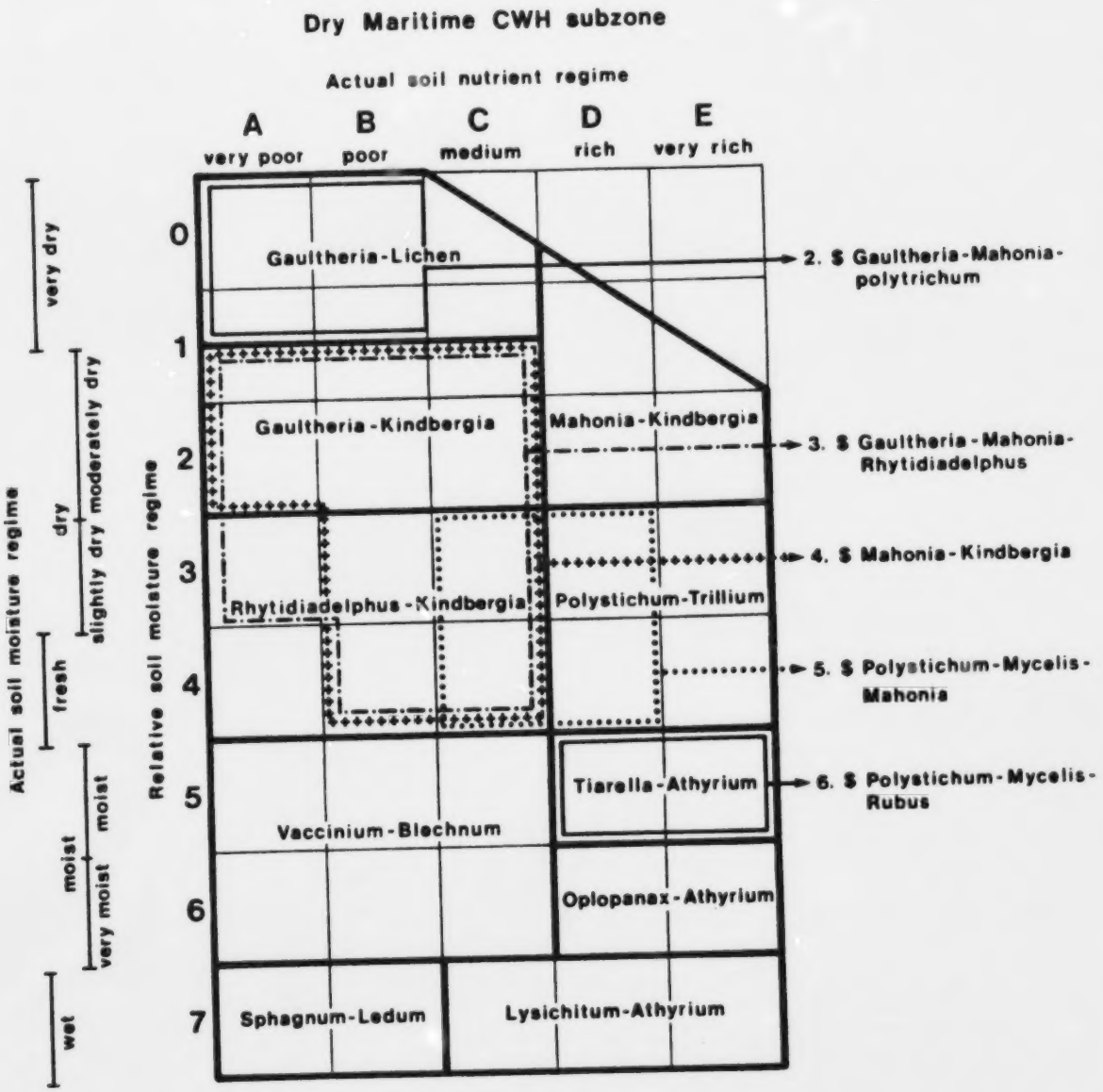

Figure 3. Edatopic grid relating vegetation units to actual SMRs and SNRs.

Table 8. Means and standard deviations (in parentheses) of Douglas-fir site index (m/50 yrs) according to actual soil moisture and soil nutrient regime in 104 candidate stands.

Actual soil moisture regime	Actual Soil Nutrient Regime				
	Very Poor	Poor	Medium	Rich	Very Rich
Very dry	20.7	20.6			
	(2.1)	(2.4)			
Moderately dry	23.5	26.6	28.5		
	(0.6)	(2.5)	(3.8)		
Slightly dry		28.5	30.5	34.5	
		(0.7)	(1.7)	(1.0)	
Fresh		32.0	34.1	36.5	
		(1.0)	(1.4)	(1.5)	
Moist				33.7	35.5
				(3.0)	(3.5)

suggests a considerable difference in site quality. Comparing climatic and edaphic charasteristics, in particular the actual SMR and SNR, and site index values (Table 7), it becomes apparent that both units have sites with similar vegetation and productivity potentials - i.e., site quality.

The final allocation of candidate and fertilized stands into site associations, series, and types will follow the results of the correlation program. The field identification of site units will be based on keys using a combination of easily recognizable site features and indicator plant species.

Spectral analysis of understory vegetation was conducted to provide a simple means for characterizing vegetation units and their sites. The analysis produced life-form, climatic, soil moisture, and soil nutrient spectra for each vegetation unit (Figures 4-7). The life-form spectra corresponds to the result of floristic differentiation; the climatic spectra repeat the contrast between the wet and dry CWH units; the soil moisture spectra produced an inconsistent indication of actual SMRs of the sites; and the soil nutrient spectra, in particular the frequency of nitrophytic species, seems to indicate increasing nitrogen availability from the Vaccinium-Gaultheria to the Polystichum-Mycelis-Rubus vegetation units.

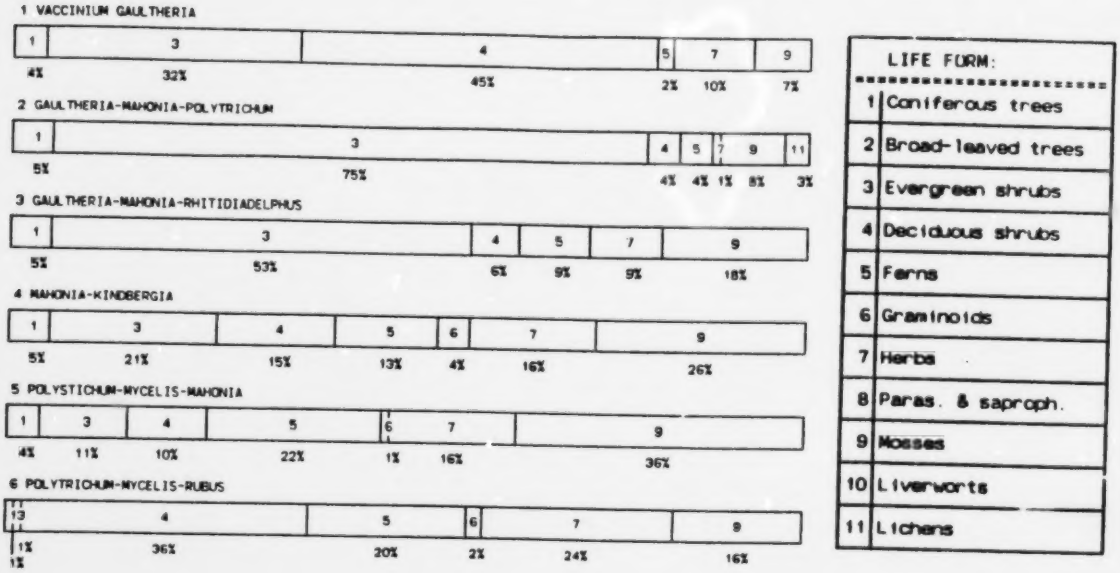

Figure 4. Spectral values for life form (based on percentage of total cover of indicator species and expressed as percent frequency).

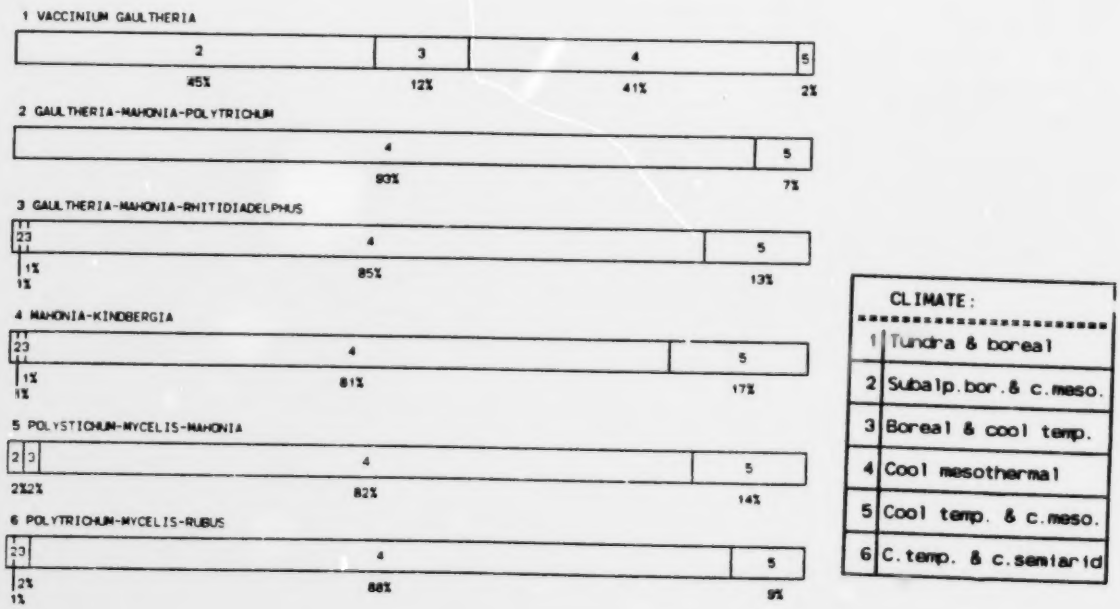

Figure 5. Spectral values for climate (based on percentage of total cover of indicator species and expressed as percent frequency).

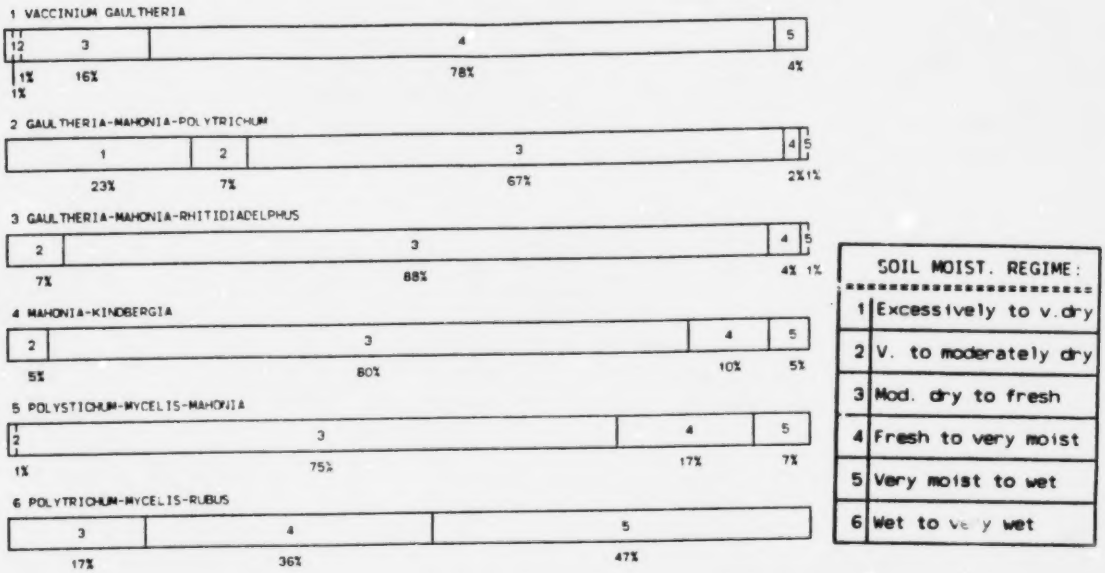

Figure 6. Spectral values for soil moisture regime (based on percentage of total cover of indicator species and expressed as percent frequency).

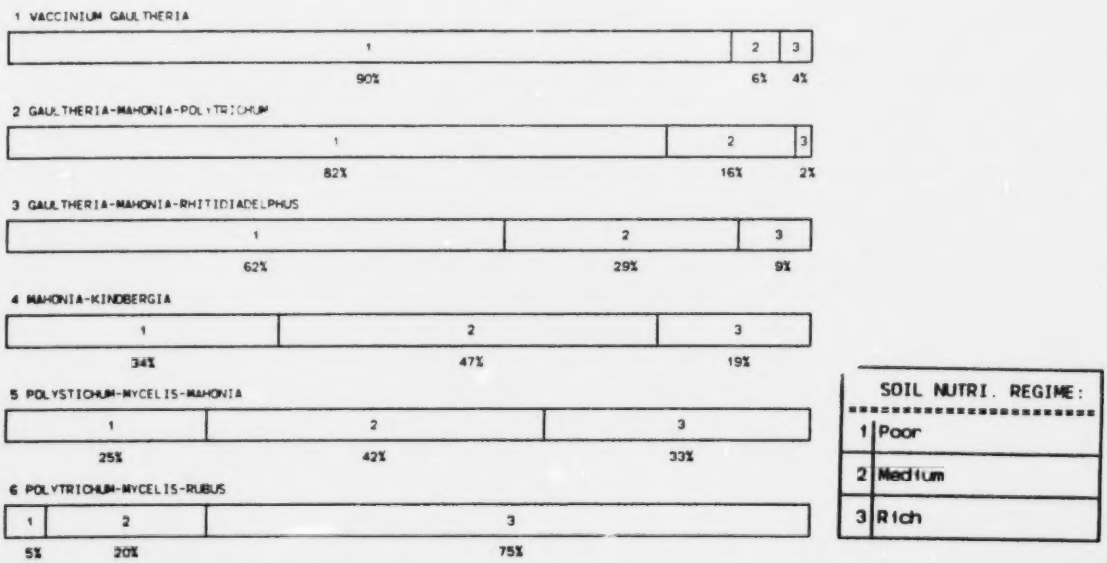

Figure 7. Spectral values for soil nutrient regime (based on percentage of total cover of indicator species and percent frequency).

» SELECTION OF STANDS AND TREATMENTS FOR FERTILIZER TRIALS

» Diagnosis of Stand Nutrient Status

The nutrient status of each candidate stand was assessed through the use of foliar analysis. The levels of eleven nutrient elements: N, P, K, Ca, Mg, S, Cu, Zn, Fe, Mn, B, SO_4-S and active-Fe were examined for potential deficiencies in each stand. Possible nutrient deficiencies and relative levels of nutrient sufficiency were then examined through a scoring procedure and two ranking procedures; the first based on nutrient ratios, the second on the Diagnosis and Recommendation Integrated System (DRIS) developed by Beaufils (1973) and Beaufils and Sumner (1977).

All of these diagnostic procedures are based on foliar nutrient analysis. Recognizing the limitations of such procedures, every effort was made to assess possible nutrient deficiencies diagnosed through the above foliar nutrient analysis methods in relation to stand growth performance and site nutrient status implied by the presence or absence of plant indicator species.

» Critical Limits

Foliar nutrient concentrations (dry mass basis), including the mean weight per 100 needles, are given for each stand in Table 9. A preliminary diagnosis was made using the Foliar Nutrient Analysis (FNA) program of Ballard and Carter (1986). Apparent deficiencies were then examined for interactions related to tree vigour and needle size (dilution; Morrisson 1974) using benchmark milligrams-of-nutrient/100 needles data and nutrient ratios (Carter 1985, unpublished data). A scoring procedure was then developed to rank each stand's potential for nutrient deficiency. The scores used in this procedure were based on critical limits modified from Ballard and Carter (1986) and were assigned on the premise that certain nutrients have a stronger relationship to productivity than others. Each nutrient elements' expected range of values (concentration on a dry mass basis) was divided into between two and six levels, and each level was associated with an index score. The weighting of each score was based on Beaufils' (1973) hypothesis that foliar nutrients with the lowest coefficients of variation in a select, high-productivity population are those nutrients that must be maintained within a narrow range for optimal growth.

Foliar nutrient levels in the 17 most productive stands sampled in this study were used to identify the proper weighting for each nutrient. Total N, Ca, Mg, and S had the lowest coefficients of variation in this high-productivity subsample. Foliar nutrient concentrations and contents (mg/100 needles) were also examined in relation to site index and indicator plant species groups. Total N, Mg, S, and SO_4-S showed the strongest relationships to these variables. The index values given in Table 10 reflect each nutrient's weighted importance based on these studies. The index scores for each stand sampled in the reconnaissance study are given in Table 11. Each nutrients deviation from adequacy, as defined by the critical limits given in Ballard and Carter (1986) was also used to rank nutrient elements from most to least deficient. This ranked order of nutrient sufficiency is also given in Table 11.

Table 9. Mean foliar nutrient concentrations for all stands sampled in the Reconnaissance study.

Plot No.	mg/100 needles	N	P	K	Ca	Mg	S	SO4	Cu	Zn	Mn	B	AFe
		%						ppm					
1	521	1.28	0.160	0.61	0.35	0.112	0.137	214	5	19	247	16	37
2	495	1.29	0.175	0.71	0.39	0.116	0.131	173	4	16	156	11	34
3	444	1.26	0.140	0.67	0.32	0.090	0.142	329	4	15	203	18	34
4	560	1.34	0.135	0.62	0.35	0.101	0.134	156	5	16	138	11	34
5	387	1.14	0.190	0.67	0.35	0.107	0.136	360	4	19	366	18	33
6	553	1.02	0.235	0.61	0.38	0.113	0.164	589	5	20	980	19	37
7	523	1.14	0.220	0.79	0.38	0.115	0.154	447	6	28	700	20	46
8	592	1.17	0.195	0.66	0.30	0.112	0.145	317	4	13	345	14	54
9	564	1.11	0.225	0.73	0.45	0.125	0.149	492	3	19	668	25	29
10	487	0.97	0.250	0.50	0.31	0.096	0.129	227	3	18	776	13	27
11	551	1.22	0.205	0.72	0.41	0.126	0.137	232	4	19	411	23	33
12	501	1.16	0.205	0.51	0.34	0.143	0.137	237	4	18	530	13	58
13	472	1.24	0.220	0.68	0.33	0.142	0.118	152	4	16	325	13	58
14	406	1.18	0.225	0.73	0.44	0.124	0.138	273	4	21	646	24	37
15	360	0.95	0.260	0.75	0.49	0.124	0.140	371	3	22	1805	20	29
16	410	1.26	0.210	0.74	0.38	0.135	0.112	90	4	17	108	11	33
18	571	1.30	0.200	0.72	0.34	0.122	0.118	64	4	16	342	15	37
19	436	1.31	0.250	0.69	0.37	0.135	0.132	176	4	18	546	10	37
20	440	1.18	0.220	0.67	0.42	0.134	0.130	211	4	19	372	25	39
21	512	1.09	0.225	0.81	0.35	0.123	0.164	550	3	19	531	29	30
22	500	1.20	0.205	0.79	0.40	0.119	0.157	480	3	19	349	29	29
23	476	1.01	0.205	0.75	0.41	0.123	0.153	504	3	21	380	35	29
24	492	0.98	0.220	0.74	0.39	0.126	0.134	397	3	23	754	34	33
25	479	1.25	0.135	0.78	0.41	0.117	0.177	509	3	16	280	47	50
26	421	1.15	0.175	0.63	0.43	0.139	0.125	207	3	19	669	22	33
27	416	1.18	0.205	0.66	0.44	0.149	0.134	275	3	22	906	22	50
28	445	1.29	0.205	0.54	0.39	0.148	0.137	229	3	18	628	12	37
30	435	1.20	0.285	0.80	0.38	0.117	0.150	450	4	21	941	24	33
31	419	1.17	0.250	0.75	0.48	0.140	0.141	393	4	26	743	26	29
32	430	1.29	0.230	0.74	0.49	0.142	0.155	412	4	26	363	31	33
33	412	1.16	0.215	0.83	0.46	0.139	0.146	427	4	24	862	21	45
34	462	1.20	0.175	0.74	0.46	0.147	0.152	304	5	23	388	19	45
35	447	1.23	0.215	0.72	0.44	0.190	0.134	214	4	23	463	15	66
36	418	1.16	0.235	0.75	0.44	0.168	0.144	413	5	25	660	18	180
37	358	1.20	0.220	0.76	0.43	0.140	0.127	170	4	16	421	20	62
38	479	1.18	0.280	0.72	0.52	0.151	0.141	428	4	27	1542	23	41
39	465	1.16	0.240	0.66	0.47	0.134	0.131	321	4	26	990	18	37
40	511	1.17	0.210	0.69	0.40	0.140	0.131	304	3	19	470	22	31
41	418	1.11	0.205	0.69	0.39	0.134	0.124	324	3	18	549	20	29
42	476	1.23	0.195	0.73	0.41	0.128	0.136	285	3	19	475	32	33
43	439	1.30	0.255	0.78	0.35	0.142	0.159	453	4	23	532	20	33
44	487	1.16	0.230	0.79	0.40	0.118	0.142	283	3	19	409	23	62
45	460	1.09	0.145	0.69	0.44	0.115	0.121	266	4	20	350	22	33
46	465	1.19	0.165	0.58	0.44	0.152	0.133	243	4	19	560	21	62
47	438	1.11	0.215	0.68	0.44	0.160	0.147	499	4	23	598	22	71
48	377	1.21	0.205	0.68	0.37	0.126	0.123	251	4	19	366	12	29
49	379	1.18	0.200	0.65	0.35	0.128	0.136	309	4	19	450	13	29
50	503	1.27	0.225	0.75	0.41	0.137	0.136	354	5	18	426	12	29
51	318	1.13	0.245	0.49	0.37	0.128	0.118	261	4	20	713	11	33
52	501	1.27	0.215	0.68	0.38	0.133	0.123	213	3	20	593	17	33
53	484	1.19	0.185	0.76	0.35	0.133	0.138	360	3	16	499	19	33
54	475	1.16	0.175	0.75	0.35	0.125	0.118	317	4	17	403	19	29
55	591	1.25	0.185	0.60	0.34	0.132	0.111	159	4	16	537	16	33

continued...

PLOT No.	mg/100 needles	N	P	K	Ca	Mg	S	SO4	Cu	Zn	Mn	B	AFe
		%						ppm					
56	595	1.33	0.135	0.69	0.37	0.137	0.132	328	4	18	395	26	33
57	638	1.08	0.180	0.75	0.39	0.126	0.105	155	3	18	390	13	34
58	491	1.37	0.155	0.67	0.49	0.130	0.112	155	6	18	295	20	33
59	443	1.05	0.220	0.48	0.38	0.118	0.110	189	4	16	493	20	111
60	428	1.21	0.150	0.67	0.37	0.128	0.144	421	5	19	362	24	120
61	454	0.98	0.250	0.80	0.37	0.125	0.129	428	2	19	899	20	33
101	510	1.08	0.200	0.79	0.43	0.092	0.100	175	4	19	260	26	48
102	610	1.28	0.200	0.61	0.31	0.116	0.095	75	4	16	145	11	46
103	750	1.15	0.200	0.53	0.35	0.100	0.089	105	4	18	135	11	42
104	590	1.22	0.230	0.74	0.42	0.137	0.123	385	4	20	470	24	36
105	500	0.98	0.270	0.72	0.47	0.140	0.130	555	3	19	705	28	23
106	430	1.29	0.220	0.90	0.24	0.088	0.170	815	4	16	275	19	47
107	490	1.26	0.170	0.84	0.36	0.122	0.152	575	4	15	780	30	31
108	630	1.25	0.220	0.76	0.40	0.137	0.125	355	4	23	935	29	41
109	490	1.30	0.240	0.66	0.39	0.127	0.123	345	4	21	445	18	45
110	560	1.26	0.200	0.63	0.29	0.114	0.103	135	5	15	330	14	43
111	479	1.32	0.200	0.61	0.35	0.098	0.112	185	4	18	175	20	65
112	423	1.27	0.180	0.61	0.31	0.128	0.101	185	6	16	245	25	62
113	443	1.23	0.220	0.61	0.33	0.126	0.100	135	4	16	255	13	91
114	550	1.13	0.320	0.72	0.41	0.129	0.145	715	3	26	805	27	57
115	640	1.20	0.260	0.73	0.42	0.133	0.121	355	4	20	520	24	31
116	550	1.14	0.280	0.78	0.41	0.116	0.118	380	6	21	530	29	33
117	520	1.39	0.190	0.76	0.51	0.119	0.120	200	7	21	470	19	46
118	607	1.18	0.250	0.70	0.43	0.139	0.119	430	4	21	605	17	42
119	500	1.19	0.220	0.74	0.47	0.113	0.117	320	4	19	530	30	34
120	566	1.01	0.240	0.64	0.46	0.130	0.118	505	4	24	760	25	32
121	610	1.15	0.240	0.77	0.43	0.122	0.131	425	3	21	940	27	36
122	550	1.15	0.200	0.61	0.37	0.120	0.114	285	4	21	285	23	38
123	440	1.27	0.230	0.69	0.43	0.141	0.121	325	4	23	900	21	51
124	440	1.09	0.230	0.67	0.51	0.153	0.106	315	4	22	1375	16	39
125	500	1.22	0.240	0.71	0.39	0.130	0.120	340	4	20	530	27	36
126	580	1.39	0.210	0.64	0.36	0.152	0.130	300	5	23	450	25	51
127	380	1.00	0.240	0.62	0.50	0.116	0.106	340	5	24	1545	27	34
128	380	1.10	0.230	0.68	0.48	0.124	0.120	385	4	21	1180	23	31
129	640	1.12	0.220	0.68	0.42	0.125	0.109	385	5	25	490	24	50
130	520	1.20	0.220	0.69	0.40	0.116	0.108	265	5	19	785	25	45
131	430	0.96	0.250	0.65	0.38	0.135	0.108	410	5	20	940	30	30
132	550	1.12	0.210	0.63	0.38	0.137	0.111	250	3	23	610	23	34
133	420	1.15	0.220	0.63	0.34	0.143	0.126	410	4	22	455	22	41
134	600	1.13	0.220	0.66	0.38	0.148	0.135	485	4	23	660	31	43
135	620	1.03	0.220	0.53	0.41	0.104	0.086	155	4	17	515	18	33
136	910	1.15	0.150	0.53	0.29	0.102	0.080	55	4	16	350	11	29
137	572	1.16	0.140	0.57	0.39	0.129	0.107	280	4	20	445	23	40
138	612	1.30	0.120	0.90	0.35	0.098	0.102	175	4	22	210	16	42
139	470	1.03	0.160	0.76	0.33	0.108	0.098	305	4	17	335	16	40
140	455	0.96	0.160	0.59	0.45	0.123	0.107	65	3	22	275	12	46
141	482	0.98	0.140	0.65	0.37	0.116	0.103	300	5	17	255	19	36
142	716	1.12	0.140	0.55	0.43	0.124	0.102	315	4	18	375	16	39
143	576	1.21	0.150	0.55	0.37	0.114	0.100	175	4	17	375	17	32
144	554	1.19	0.170	0.73	0.35	0.118	0.119	340	4	17	245	20	32
145	455	1.46	0.190	0.67	0.36	0.122	0.098	35	5	19	250	12	58

» Diagnosis and Recommendation Integrated System (DRIS)

The DRIS system is a relatively recent development in nutritional research in agriculture and is being adopted widely throughout the world (Letzsch 1984). In forestry, however, DRIS has only been applied on a small scale, investigative basis, on *Pinus radiata, Populus deltoides, Eucalyptus saligna,* and *Pinus patula* (Schutz and de Villiers 1986).

DRIS uses nutrient concentrations and ratios to interpret tissue analyses. This system has been found reliable in diagnosing nutrient deficiencies regardless of the tissue sampled or the season of sampling (Sumner 1977a; 1977b). In addition, DRIS is based on nutrient balance, indicating not only the nutrient most likely to be limiting, but also the order in which other nutrients are likely to become limiting (Beverly *et al.* 1984). Use of DRIS requires four steps: (1) the creation of a data bank; (2) development of DRIS norms; (3) calculation of indices; and, (4) testing of the norms (Schutz and de Villiers 1986). These steps are outlined below.

(1) Creation of a Data Bank

The data bank used for development of the DRIS norms included 104 candidate stands. These stands were divided into low (<23 m), medium (23-30 m), and high (>33 m) productivity classes on the basis of their site index (m/50 years; Bruce 1981).

(2) Development of DRIS Norms

Table 10. Index scores assigned to foliar nutrient concentration levels for calculation of each sites' index of nutrient deficiency.

Nutrient	Critical limit	Score	Nutrient	Critical limit	Score
N %	>1.40	0	Mg %	>0.12	0
	1.33 - 1.40	1		0.10 - 0.12	1
	1.25 - 1.32	2		0.08 - 0.099	2
	1.15 - 1.24	4		<0.08	3
	1.05 - 1.14	6			
	<1.05	9	Cu ppm	>3.0	0
				2.5 - 3.0	1
P %	>0.15	0		<2.5	2
	0.12 - 0.15	2			
	<0.12	4	Zn ppm	>15	0
				12 - 15	1
K %	>0.65	0		9 - 11.9	2
	0.54 - 0.65	1		< 9	3
	<0.54	2			
			B ppm	>15	0
S %	>0.16	0		12 - 15	1
	0.14 - 0.16	1		10 - 11.9	2
	0.12 - 0.139	3		6 - 9.9	3
	<0.12	5		< 6	5
SO_4-S ppm	>200	0	AFe ppm	>30	0
	150 - 200	1		<30	1
	100 - 149	2			
	<100	4	Mn ppm	>25	0
				<25	1
Ca %	>0.25	0			
	0.20 - 0.25	1			
	<0.20	2			

Table 11. Index scores for each stand with the ranked order of nutrient sufficiency based on each nutrient deviation from adequacy using critical limits.

Plot no	Index Score	Order of Nutrient Sufficiency Most deficient -- Least deficient	Plot No.	Index Score	Order of Nutrient Sufficiency Most deficient -- Least deficient
1	6	S N K MG P AFE B CA ZN CU MN	55	12	S N K AFE MG P ZN B CA CU MN
2	10	S B N MG K AFE P ZN CU CA MN	56	7	S P N K AFE MG CU ZN CA B MN
3	8	MG N S P K ZN CA AFE B CU MN	57	14	S N B AFE MG K CU P ZN CA MN
4	12	S B P MG N K AFE ZN CA CU MN	58	8	S N K P AFE MG ZN B CA CU MN
5	10	N S MG K AFE P CA B CU ZN MN	59	22	S K N MG ZN CU P CA B AFE MN
6	11	N K S MG AFE CA B P ZN CU MN	60	6	N S P K MG CA ZN CU B AFE MN
7	8	N S MG K P CA AFE B ZN CU MN	61	12	N CU S MG K AFE CA ZN B P MN
8	7	N S K MG ZN B CA P CU AFE MN	101	14	S N MG K P CU ZN AFE CA B MN
9	8	N S AFE K MG CU P ZN CA B MN	102	15	S B K N MG CA P ZN AFE CU MN
10	19	N K S MG AFE CU B CA ZN P MN	103	16	S K N MG B P CA AFE ZN CU MN
11	7	S N AFE K MG CU P ZN CA B MN	104	7	S N K AFE MG P CU ZN CA B MN
12	10	K N S B MG CU CA P ZN AFE MN	105	13	N AFE S K CU MG ZN P CA B MN
13	12	S N B K MG CA ZN P CU AFE MN	106	5	MG N CA S ZN K P CU AFE B MN
14	7	N S K MG AFE CU P ZN CA B MN	107	4	N S AFE MG P ZN K CA CU B MN
15	10	N S AFE MG K CU B P ZN CA MN	108	5	S N K MG AFE P CU CA ZN B MN
16	13	S B N K MG AFE ZN P CA CU MN	109	5	S N K MG AFE B CU CA P ZN MN
18	12	S N K MG B AFE ZN P CU CA MN	110	13	S N K MG CA B ZN P AFE CU MN
19	7	B S N K MG AFE CU ZN CA P MN	111	11	S MG K N P CA ZN CU B AFE MN
20	7	S N K MG CU AFE P ZN CA B MN	112	9	S K N MG P CA ZN AFE B CU MN
21	7	N AFE S MG CU K CA P ZN B MN	113	13	S N K B MG CA ZN P CU AFE MN
22	8	N CU AFE S MG K P ZN CA B MN	114	8	N S K CU MG CA AFE P ZN B MN
23	10	N S AFE MG K CU P CA ZN B MN	115	7	S N AFE K MG CU ZN CA P B MN
24	12	N S AFE K MG CU P CA ZN B MN	116	12	S N MG AFE K CA ZN P CU B MN
25	7	N P MG S CU K ZN AFE CA B MN	117	6	S N MG K P AFE B ZN CA CU MN
26	10	S N K AFE CU P MG ZN CA B MN	118	9	S N K MG AFE B CU P CA ZN MN
27	7	N S K CU MG P CA B ZN AFE MN	119	10	S N MG AFE K P CU ZN CA B MN
28	8	K S N B CU AFE MG P ZN CA MN	120	15	S N K AFE MG CU P CA ZN B MN
30	6	N S MG AFE K CA CU ZN P B MN	121	10	S N MG CU K AFE P CA ZN B MN
31	5	N S AFE K CU MG P CA ZN B MN	122	11	S N K MG AFE P CA CU ZN B MN
32	3	N S AFE K MG CU P CA ZN B MN	123	5	S N K MG P CU AFE CA B ZN MN
33	5	N S MG K P AFE CU B CA ZN MN	124	11	S N K B MG P CU AFE ZN CA MN
34	5	N S K P MG AFE B CU CA ZN MN	125	7	S N K MG AFE CU CA P ZN B MN
35	8	S N K B P CU MG CA ZN AFE MN	126	5	S K N MG P CA AFE ZN CU B MN
36	5	N S K B MG P CA CU ZN AFE MN	127	16	S N K MG AFE P CU CA ZN B MN
37	9	S N K MG ZN P CU B CA AFE MN	128	9	S N AFE K MG P CU ZN B CA MN
38	5	N S K MG AFE CU P B CA ZN MN	129	11	S N K MG P AFE CA CU B ZN MN
39	7	N S K AFE MG CU B P CA ZN MN	130	10	S N MG K P AFE ZN CA CU B MN
40	7	S N K AFE CU MG P ZN CA B MN	131	15	S N K AFE MG CA P ZN CU B MN
41	11	S N CU AFE K MG P ZN CA B MN	132	13	S N K AFE CU MG P CA ZN B MN
42	7	S N AFE K CU MG P ZN CA B MN	133	8	S N K MG AFE CA P CU ZN B MN
43	3	S N AFE K MG CU CA B P ZN MN	134	9	N S K MG AFE P CA CU ZN B MN
44	6	N S MG CU K P ZN AFE CA B MN	135	18	S N K MG AFE ZN P B CU CA MN
45	12	S N P MG K AFE CU ZN CA B MN	136	20	S K N B MG AFE P CA ZN CU MN
46	8	S N K P CU MG ZN B CA AFE MN	137	12	S N K P MG AFE CU CA ZN B MN
47	7	N S K P MG CU CA B ZN AFE MN	138	12	S P MG N B AFE K CA CU ZN MN
48	9	S N B AFE K MG P CA CU ZN MN	139	15	S N MG P K CA AFE B ZN CU MN
49	8	N S K AFE B MG P CU CA ZN MN	140	21	S N K B P MG CU AFE CA ZN MN
50	8	S N AFE B K MG P ZN CA CU MN	141	18	S N P K MG AFE ZN CA B CU MN
51	15	S K N B MG AFE CU CA P ZN MN	142	14	S N K P MG AFE B ZN CU CA MN
52	5	S N K AFE CU MG B P CA ZN MN	143	14	S K N P AFE MG ZN B CA CU MN
53	7	N S CU AFE K MG P ZN CA B MN	144	10	N AFE MG K P CA ZN CU B S MN
54	9	S N AFE MG K P CU ZN CA B MN	145	19	S B K N MG P CA ZN AFE CU MN

Each stand's foliar data was then expressed as concentrations (dry mass basis) and as weight per 100 needles and all possible ratios were calculated (i.e., 2 ratios for each pair of nutrient elements). For each site-index-based subpopulation the mean ($\bar{x}$), standard deviation (sd), and variance (s^2) were calculated for each nutrient concentration and ratio. A variance ratio (s^2 for low-productivity population/s^2 for high-productivity population) was calculated for each concentration and nutrient ratio. The nutrient ratio with the larger variance ratio was selected from each of the two ratios involving each pair of nutrients. The mean and coefficient of variation (CV) values for the selected ratios in the high-productivity population were used in calculating the DRIS indices (Table 12).

(3) Calculation of DRIS Indices

The methodology employed in calculation of the DRIS indices has been described by several other authors (Beaufils 1971 and 1973; Beverly *et al.* 1984, Sumner 1977b; Schutz and de Villiers 1986). The following excerpt from Beverly *et al.* (1984) gives a concise description of the calculation procedure. "In general, the deviation of each nutrient ratio in an unknown sample from the corresponding reference value (x, Table 12) is divided by the corresponding CV value to assign more weight to those ratios with less inherent variation. If the observed ratio value (X) is larger than the reference value x, the weighted deviation (WD) is calculated by equation [1]

$$WD_x = 100\left(\frac{X}{x} - 1\right)\frac{10}{CV_x} \qquad [1]$$

If the observed value X, is less than x, equation 2 is used.

$$WD_x = 100\left(1 - \frac{X}{x}\right)\frac{10}{CV_x} \qquad [2]$$

Table 12. Mean and coefficient of variation found in the high yielding population for all ratios use in developing the DRIS indices.

Ratio	K/N	CA/N	S/N	N/SO4	MN/N	P/Cu	ZN/P	MG/K	S/K
Mean	0.586	0.335	0.103	61.5	0.043	500	0.0090	0.180	0.176
CV %	10.8	15.6	11.7	81.2	59.4	21.6	15.1	11.1	10.2
Ratio	SO4/K	K/Cu	MN/K	Ca/Mg	Ca/SO4	Ca/CU	Mg/SO4	Mg/Cu	S/CU
Mean	0.18	1677	0.071	3.20	19.2	948	6.13	301	296
CV %	10.2	18.9	53.5	11.4	69.1	16.1	76.4	21.2	22.0
Ratio	CU/SO4	ZN/SO4	ZN/CU	MN/CU	B/CU	MN/B	AFE/N	P/AFE	AFE/K
Mean	0.021	0.087	4.44	117.7	4.67	23.8	0.0028	62.4	0.0049
CV %	68.2	65.3	20.3	54.2	37.0	33.7	4.1	20.6	14.0
Ratio	AFE/CA	AFE/MG	AFE/S	AFE/SO4	AFE/CU	AFE/ZN	MN/AFE	B/AFE	
Mean	0.009	0.027	0.028	0.17	8.14	1.85	14.7	0.59	
CV %	13.8	13.9	17.2	80.3	20.2	14.9	54.5	39.1	

The algebraic sign of the weighted deviation depends on its application. The sign is as calculated when the weighted deviation is used to determine the index value for the nutrient in the numerator; in calculating the index value for the nutrient in the denominator, the sign is changed. The index value for any nutrient is the mean of the weighted deviations for all ratios involving that nutrient. Thus, the calculated DRIS indices provide a measure of the nutrient balance within the sample of interest. Since deviations are measured, the DRIS indices sum to zero. The nutrient with the most negative index is considered the most relatively insufficient, or most limiting." DRIS indices and each stand's order of relative nutrient sufficiency as identified by DRIS are given in Table 13.

(4) Testing of the Norms

Relationship(s) between the DRIS order of nutrient sufficiency and response to fertilizers prescribed on the basis of DRIS diagnoses will be examined using first-year response measures (graphical analysis and shoot-length ratios) and later volume increment measures.

» Selection of Stands

Candidate stands were selected on the basis of their areal extent, uniformity of site and stand characteristics, and representation of major segments of the environmental gradient. Selection of stands for fertilizer trials did not focus on stands with the greatest apparent deficiencies. Instead, the aim was to select stands that would represent the complete range of site/stand conditions found in coastal immature Douglas-fir ecosystems with treatments based on the stand nutrient diagnosis described earlier. The distribution of stands selected for the establishment of fertilizer trials in relation to site quality (biogeoclimatic units, actual SMR, and actual SNR) is given in Table 14. This resulted in a wide, relatively continuous range of site indices in the selected stands (Figure 8).

» Selection of Fertilizer Treatments

The nutrients identified as being most limiting in both the DRIS analyses and the ranked order of nutrient sufficiency based on critical limits were compared to determine which nutrient(s) were most likely to be limiting growth in each stand. Any nutrient identified as being potentially deficient on the basis of critical limits was included in a fertilizer treatment for that stand. Nutrients identified on the basis of DRIS and the ranked order of nutrient sufficiency analyses as being more deficient than the prescribed nutrients were also included in the treatment (with the exception of Mn which was not considered deficient in any stand). The chemical form and application rate for each fertilizer applied is given in Table 15. Sulphur application rate was adjusted in cases where sulphur was applied as part of another treatment (i.e. S applied along with Mg in $MgSO_4$).

» Fertilizer Trial Design

Each installation is designed around replicated small fixed-area plots. All plots consist of five treated trees with a minimum treatment buffer of 5.0 m around each treated tree. Treatment plots had a minimum buffer adjacent to roads and other openings in the stand of 10 m. Average plot size in the 56 installations established was approximately 25(m^2.

All installations have paired control and nitrogen treatments (225 kg N/ha; urea). Any other nutrient element(s) diagnosed as potentially deficient was added in a third treatment along with nitrogen. This resulted in most installations having 30 treated trees. The treatments applied in each of the 56 installations are given in Table 16. In two installations (No. 7 and 61), nitrogen and sulphur were applied in a completely randomized block design. These installations each had 40 treated trees. A third installation (No. 38) was given an additional replicated treatment of nitrogen and sulphur (the only two nutrients diagnosed as potentially deficient) at one-half the prescribed dosage (112 kg N/ha; 25 kg S/ha). This treatment will be repeated in 1988, and 1989 in an attempt to identify a differential response to repeated low level treatments.

Table 13. DRIS indices and order of relative nutrient sufficiency for each stand.

Stand	N	P	K	CA	MG	S	SO4	CU	ZN	MN	B	AFE	DRIS ORDER OF RELATIVE NUTRIENT SUFFICIENCY Most Deficient ——— Least Deficient									
1	8	-20	-13	-10	-5	9	5	9	4	-18	-7	10	P	Mn	K	Ca	B	Mg	Zn	SO4	N	S	Cu	AFe
2	13	-5	6	-1	-4	3	-1	6	-5	-36	-15	7	Mn	B	P	Zn	Mg	SO4	Ca	S	K	Cu	AFe	N
3	9	-19	0	-11	-20	12	13	6	-6	-28	-1	8	Mn	Mg	P	Ca	Zn	B	K	Cu	AFe	N	S	SO4
4	22	-26	-6	-6	-10	7	0	17	0	-44	-17	10	Mn	P	B	Mg	Ca	K	SO4	Zn	S	AFe	Cu	N
5	-4	-4	-2	-6	-8	12	13	-0	-0	-5	-2	1	Mg	Ca	Mn	P	N	K	B	Zn	Cu	AFe	S	SO4
6	-30	3	-23	-7	-11	31	30	-2	-8	23	-3	6	N	K	Mg	Zn	Ca	B	Cu	P	AFe	Mn	SO4	S
7	-29	-19	-2	-15	-21	7	12	10	7	5	-7	17	N	Mg	P	Ca	B	K	Mn	S	Zn	Cu	SO4	AFe
8	-25	-2	-12	-27	-10	10	12	-6	-33	-8	-13	52	Zn	Ca	N	B	K	Mg	Mn	Cu	P	S	SO4	AFe
9	-10	13	3	14	-1	25	21	-24	3	9	11	-15	Cu	AFe	N	Mg	K	Zn	Mn	B	P	Ca	SO4	S
10	-5	30	-19	2	2	32	12	-21	5	27	-2	-4	Cu	K	N	AFe	B	Ca	Mg	Zn	SO4	Mn	P	S
11	1	2	1	4	1	10	3	-9	4	-4	5	-3	Cu	Mn	AFe	N	K	Mg	P	SO4	Ca	Zn	B	S
12	-27	-9	-42	-23	12	12	9	-10	-11	5	-16	56	K	N	Ca	B	Zn	Cu	P	Mn	SO4	Mg	S	AFe
13	-19	-4	-9	-27	5	-13	-5	-1	-21	-11	-19	54	Ca	Zn	B	N	S	Mn	K	SO4	P	Cu	Mg	AFe
14	-10	3	0	7	-4	9	5	-13	5	6	5	3	Cu	N	Mg	K	AFe	P	B	SO4	Zn	Mn	Ca	S
15	-33	20	4	25	-2	23	12	-30	10	63	5	-16	N	Cu	AFe	Mg	K	B	Zn	SO4	P	S	Ca	Mn
16	21	4	16	-1	10	-9	-17	9	-0	-61	-14	7	Mn	SO4	B	S	Ca	Zn	P	AFe	Cu	Mg	K	N
18	12	3	5	-5	7	-5	-24	-2	-1	-7	-5	12	SO4	Mn	B	S	Ca	Cu	Zn	P	K	Mg	N	AFe
19	4	14	-5	-6	8	5	-0	-7	-5	10	-18	7	B	Cu	Ca	Zn	K	SO4	N	S	AFe	Mg	Mn	P
20	-7	3	-5	2	4	6	2	-10	0	-8	6	10	Cu	Mn	N	K	Zn	SO4	Ca	P	Mg	B	S	AFe
21	-14	12	9	-7	-0	31	26	-24	1	1	15	-11	Cu	N	AFe	Ca	Mg	Mn	Zn	K	P	B	SO4	S
22	-0	11	12	8	-1	30	22	-34	8	-10	19	-14	Cu	AFe	Mn	Mg	N	Ca	Zn	P	K	B	SO4	S
23	-18	5	8	8	-1	29	23	-24	11	-9	22	-13	Cu	N	AFe	Mn	Mg	P	K	Ca	Zn	B	SO4	S
24	-24	5	7	4	1	16	13	-25	13	10	19	-2	Cu	N	AFe	Mg	Ca	P	K	Mn	Zn	SO4	S	B
25	-24	-29	-1	-3	-15	27	23	-27	-13	-31	26	33	Mn	P	Cu	N	Mg	Zn	Ca	K	SO4	B	S	AFe
26	-3	-5	-8	9	12	10	2	-17	10	10	6	-0	Cu	K	P	N	AFe	SO4	B	Ca	Mn	Zn	S	Mg
27	-6	-7	-14	2	9	7	6	-26	7	17	2	18	Cu	K	P	N	Ca	B	SO4	Zn	S	Mg	Mn	AFe
28	5	5	-30	-2	21	18	8	-16	0	14	-10	8	K	Cu	B	Ca	Zn	P	N	SO4	AFe	Mn	S	Mg
30	-10	18	4	-5	-8	14	16	-9	-2	16	5	-8	N	Cu	Mg	AFe	Ca	Zn	K	B	S	SO4	Mn	P
31	-11	10	3	14	5	15	11	-18	19	10	9	-17	Cu	AFe	N	K	Mg	B	P	Mn	SO4	Ca	S	Zn
32	-5	2	-2	11	4	19	13	-18	17	-11	13	-9	Cu	Mn	AFe	N	K	P	Mg	Ca	B	SO4	Zn	S
33	-14	-8	3	1	-5	6	10	-12	5	13	-2	7	N	Cu	P	Mg	B	Ca	K	Zn	S	AFe	SO4	Mn
34	-7	-24	-8	-0	1	10	6	-1	7	-7	-5	10	P	K	Mn	N	B	Cu	Ca	Mg	SO4	Zn	S	AFe
35	-2	-18	-16	-15	18	-7	-2	-11	-2	-3	-16	36	P	K	B	Ca	Cu	S	Mn	N	SO4	Zn	Mg	AFe
36	-10	-66	-47	-61	-34	-44	6	-17	-48	-5	-46	157	P	Ca	Zn	K	B	S	Mg	Cu	N	Mn	SO4	AFe
37	-2	-5	-3	-7	-5	-10	-5	-7	-23	-7	-7	37	Zn	S	Mn	B	Ca	Cu	P	Mg	SO4	K	N	AFe
38	-15	7	-12	9	2	8	11	-17	9	39	2	-3	Cu	N	K	AFe	B	Mg	P	S	Zn	Ca	SO4	Mn
39	-2	2	-4	10	2	8	8	-12	16	-11	-1	-1	Cu	Mn	K	N	B	AFe	P	Mg	SO4	S	Ca	Zn
40	-3	8	-1	3	12	12	8	-18	5	0	6	-4	Cu	AFe	N	K	Mn	Ca	Zn	B	P	SO4	S	Mg
41	-6	13	5	7	13	13	10	-28	8	6	7	-6	Cu	AFe	N	K	Mn	Ca	B	Zn	SO4	P	S	Mg
42	-3	3	3	5	3	12	7	-20	5	-3	17	-2	Cu	Mn	N	AFe	P	K	Mg	Zn	Ca	SO4	S	B
43	-4	11	-0	-13	9	19	17	-15	8	2	2	-7	Cu	Ca	AFe	N	K	Mn	B	Zn	Mg	P	SO4	S
44	-7	-0	3	-6	-16	3	5	-25	-12	-8	0	37	Cu	Mg	Zn	Mn	N	Ca	P	B	K	S	SO4	AFe
45	-6	-22	5	12	-6	4	4	-7	14	-8	4	1	P	Mn	Cu	Mg	N	AFe	S	SO4	B	K	Ca	Zn
46	-1	-28	-31	-6	7	3	5	-14	-8	1	-4	39	K	P	Cu	Zn	Ca	B	N	Mn	S	SO4	Mg	AFe
47	-12	-20	-22	-15	0	4	16	-15	-8	1	-7	39	K	P	Cu	Ca	N	Zn	B	Mg	Mn	S	SO4	AFe
48	1	3	1	-3	5	4	4	2	3	-2	-10	-5	B	AFe	Ca	Mn	K	N	Cu	P	Zn	SO4	S	Mg
49	-1	3	-6	-5	9	16	10	-6	4	3	-5	-5	K	Cu	Ca	AFe	B	N	Mn	P	Zn	Mg	SO4	S
50	-2	7	2	-1	4	7	9	4	-4	0	-10	-10	B	AFe	Zn	N	Ca	Mn	K	Cu	Mg	S	P	SO4
51	3	12	-30	-2	13	11	9	-6	3	20	-11	3	K	B	Cu	Ca	AFe	N	Zn	SO4	S	P	Mg	Mn
52	2	7	-1	0	10	4	2	-17	9	7	1	0	Cu	K	AFe	Ca	B	SO4	N	S	P	Mn	Zn	Mg
53	-4	3	6	-7	7	12	12	-16	-6	2	3	1	Cu	Ca	Zn	N	AFe	Mn	B	P	K	Mg	SO4	S
54	-2	-2	11	-5	4	1	7	-5	-0	-3	2	-5	Cu	Ca	AFe	Mn	N	P	Zn	S	B	Mg	SO4	K
55	8	-1	-11	-10	12	-3	-2	3	-5	5	-4	4	K	Ca	Zn	B	S	SO4	P	Cu	AFe	Mn	N	Mg
56	4	-23	-3	-7	9	6	9	-7	6	-7	8	1	P	Cu	Ca	Mn	K	AFe	N	Zn	S	B	Mg	SO4
57	-3	-2	16	5	4	-7	-6	-12	7	-1	-6	6	Cu	S	B	SO4	N	P	Mn	Mg	Ca	AFe	Zn	K
58	9	-24	-3	8	-2	-13	-6	17	2	-16	-3	-0	P	Mn	S	SO4	K	B	Mg	AFe	Zn	Ca	N	Cu
59	2	-25	-58	-33	-27	-29	0	-17	-53	-5	-18	123	K	Zn	Ca	S	Mg	P	B	Cu	Mn	SO4	N	AFe
60	-2	-80	-35	-48	-35	-19	12	-8	-41	-22	-15	117	P	Ca	Zn	Mg	K	Mn	S	B	Cu	N	SO4	AFe
61	-19	31	21	8	6	19	18	-55	8	25	11	-1	Cu	N	AFe	Mg	Ca	Zn	B	SO4	S	K	Mn	P

Table 13. continued.....

Stand	N	P	K	CA	MG	S	SO4	CU	ZN	MN	B	AFE	DRIS ORDER OF RELATIVE NUTRIENT SUFFICIENCY Most Deficient ---------- Least Deficient										
101	-4	-15	-4	-7	-11	-17	6	3	3	-3	-2	17	S	P	Mg	Ca	N	K	Mn	B	Cu	Zn	SO4	AFe
102	-1	-6	-2	-6	-13	-18	1	5	-8	8	0	13	S	Mg	Zn	Ca	P	K	N	B	SO4	Cu	Mn	AFe
103	-13	8	-2	-5	5	-4	11	5	-2	16	8	-12	N	AFe	Ca	S	K	Zn	Cu	Mg	P	B	SO4	Mn
104	-1	1	-3	0	12	1	3	-19	17	6	7	0	Cu	K	N	Ca	AFe	S	P	SO4	Mn	B	Mg	Zn
105	-1	-4	-12	-19	10	3	13	-5	2	-2	1	8	Ca	K	Cu	P	Mn	N	B	Zn	S	AFe	Mg	SO4
106	-7	-6	-12	-13	7	7	17	-10	3	4	8	7	Ca	K	Cu	N	P	Zn	Mn	AFe	S	Mg	B	SO4
107	-5	5	-3	-2	0	-5	11	-7	-3	5	-5	7	Cu	S	B	N	Zn	K	Ca	Mg	P	Mn	AFe	SO4
108	-5	3	8	12	-13	-5	5	-5	-1	-1	10	-2	Mg	Cu	N	S	AFe	Mn	Zn	P	SO4	K	B	Ca
109	-14	4	-4	9	-1	5	17	-8	10	11	6	-9	N	AFe	Cu	K	Mg	P	S	B	Ca	Zn	Mn	SO4
110	2	6	-6	10	-6	-17	-4	3	-3	4	-1	5	S	K	Mg	SO4	Zn	B	N	Cu	Mn	AFe	P	Ca
111	19	-13	-3	-7	6	-24	-28	15	11	-2	-11	8	SO4	S	P	B	Ca	K	Mn	Mg	AFe	Zn	Cu	N
112	3	-32	-14	-5	4	-7	5	-0	9	-3	2	13	P	K	S	Ca	Mn	Cu	B	N	Mg	SO4	Zn	AFe
113	4	-52	35	-8	-24	-29	-10	4	21	-20	-6	23	P	S	Mg	Mn	SO4	Ca	B	N	Cu	Zn	AFe	K
114	-4	-17	19	-11	-12	-20	2	2	-4	-8	-6	16	S	P	Mg	Ca	Mn	B	Zn	N	SO4	Cu	AFe	K
115	-3	-23	-6	20	4	-3	-26	-12	26	-10	-12	28	SO4	P	Cu	B	Mn	K	N	S	Mg	Ca	Zn	AFe
116	-5	-30	4	-5	-6	-11	5	15	-2	-19	-3	9	P	Mn	S	Mg	Ca	N	B	Zn	K	SO4	AFe	Cu
117	2	-28	-14	3	-0	-8	7	2	2	-4	-5	13	P	K	S	B	Mn	Mg	N	Cu	Zn	Ca	SO4	AFe
118	10	-16	-10	-1	2	-9	-1	5	4	-4	-2	5	P	K	S	Mn	B	Ca	SO4	Mg	Zn	AFe	Cu	N
119	-57	-8	-101	-8	-3	294	63	-18	-2	-20	1	-22	K	N	AFe	Mn	Cu	P	Ca	Mg	Zn	B	SO4	S
120	31	-22	-5	-10	1	-39	-70	21	9	-23	-24	50	SO4	S	B	Mn	P	Ca	K	Mg	Zn	Cu	N	AFe
121	-3	14	4	2	2	-1	8	-6	-0	0	5	-8	AFe	Cu	N	S	Zn	Mn	Mg	Ca	K	B	SO4	P
122	-7	9	9	-3	-14	-9	7	13	-6	-3	4	-8	Mg	S	AFe	N	Zn	Ca	Mn	B	SO4	K	P	Cu
123	3	-26	-2	4	-22	-21	-5	24	-4	-6	-10	11	P	Mg	S	B	Mn	SO4	Zn	K	N	Ca	AFe	Cu
124	3	1	-9	-9	-4	-4	8	-5	-2	-3	-4	14	Ca	K	Cu	B	S	Mg	Mn	Zn	P	N	SO4	AFe
125	13	-5	-6	-28	-3	-20	-7	17	-17	-10	-13	22	Ca	S	Zn	B	Mn	SO4	K	P	Mg	N	Cu	AFe
126	16	-17	-12	-19	-27	-20	-2	0	-15	-46	-7	56	Mn	Mg	S	Ca	P	Zn	K	B	SO4	Cu	N	AFe
127	14	-29	-17	-40	-6	-34	-4	24	-27	-32	-5	47	Ca	S	Mn	P	Zn	K	Mg	B	SO4	N	Cu	AFe
128	12	-19	-22	-40	-15	-43	-10	-3	-39	-26	-31	96	S	Ca	Zn	B	Mn	K	P	Mg	SO4	Cu	N	AFe
129	-3	-9	23	9	-34	-24	-8	-2	-3	-24	3	24	Mg	Mn	S	P	SO4	Zn	N	Cu	B	Ca	K	AFe
130	8	-16	-21	-25	8	-6	5	4	0	-7	-1	19	Ca	K	P	Mn	S	B	Zn	Cu	SO4	N	Mg	AFe
131	-17	-1	-9	16	-11	-6	6	1	7	40	4	-8	N	Mg	K	AFe	S	P	Cu	B	SO4	Zn	Ca	Mn
132	-12	5	-2	14	-4	3	10	-8	4	29	4	-10	N	AFe	Cu	Mg	K	S	B	Zn	P	SO4	Ca	Mn
133	-2	-6	-10	-6	-1	-9	5	-10	1	14	-3	17	K	Cu	S	P	Ca	B	N	Mg	Zn	SO4	Mn	AFe
134	-12	0	-7	11	7	-10	3	-10	4	41	-5	1	N	S	Cu	K	B	P	AFe	SO4	Zn	Mg	Ca	Mn
135	-1	6	1	-4	0	-3	7	-6	-1	-1	6	0	Cu	Ca	S	Zn	N	Mn	AFe	Mg	K	P	B	SO4
136	-9	-4	9	-10	-7	13	24	-6	-13	8	11	-8	Zn	Ca	N	AFe	Mg	Cu	P	Mn	K	B	S	SO4
137	-4	-5	0	-6	0	-4	6	-10	6	13	7	4	Cu	Ca	P	N	S	Mg	K	AFe	Zn	SO4	B	Mn
138	-11	11	7	7	-5	7	13	-26	5	17	11	-1	Cu	N	Mg	AFe	Zn	S	K	Ca	B	P	SO4	Mn
139	3	-7	-6	-6	-1	-3	5	-1	5	-16	2	8	Mn	P	K	Ca	S	Mg	Cu	B	N	Zn	SO4	AFe
140	-3	4	3	-1	1	-2	9	-6	-1	-3	4	-0	Cu	N	Mn	S	Ca	Zn	AFe	Mg	K	P	B	SO4
141	-21	33	9	22	12	21	25	-25	4	12	18	-31	AFe	Cu	N	Zn	K	Mg	Mn	B	S	Ca	SO4	P
142	-2	1	17	-55	-42	13	44	-4	-28	-20	-4	24	Ca	Mg	Zn	Mn	Cu	B	N	P	S	K	AFe	SO4
143	-14	18	-7	-9	-11	10	30	-37	2	10	6	22	Cu	N	Mg	Ca	K	Zn	B	S	Mn	P	AFe	SO4
144	24	-4	-1	-18	2	-25	-21	10	-7	-43	-19	35	Mn	S	SO4	B	Ca	Zn	P	K	Mg	Cu	N	AFe
145	18	-5	-7	-4	-9	-22	-11	11	-0	-43	-17	29	Mn	S	B	SO4	Mg	K	P	Ca	Zn	Cu	N	AFe

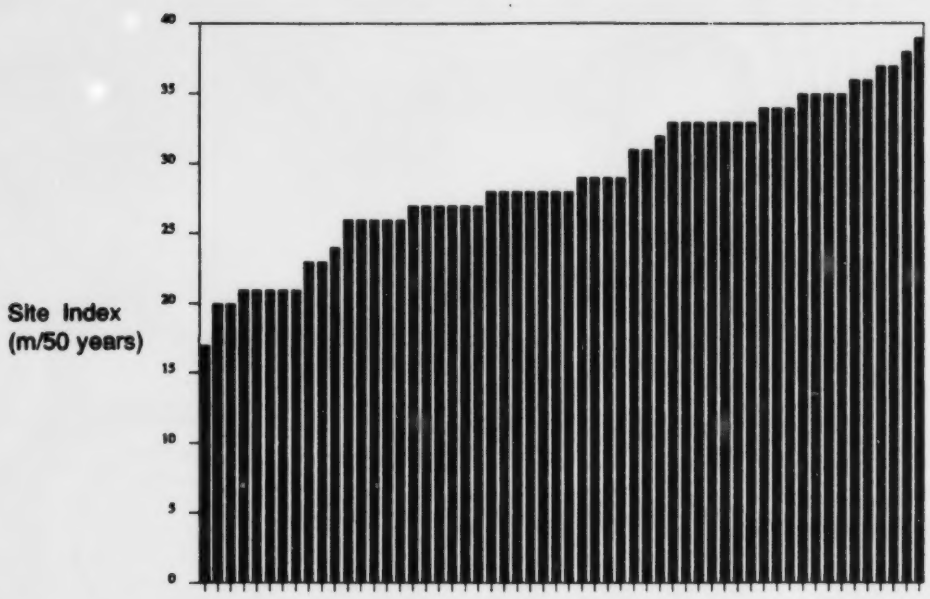

Figure 8. Distribution of site indices across in the 56 fertilized stands

Table 14 . Distribution of stands selected for fertilizer trials within each soil moisture and nutrient regime.

Actual Soil Moisture Regime	Actual Soil Nutrient Regime				
	Very Poor	Poor	Medium	Rich	Very Rich
Very Dry	3	5			
Moderately Dry		18	3		
Slightly Dry	1	1	4	6	
Fresh		3	4	3	
Moist				4	1

Table 15. Chemical form and application level for each nutrient element.

Nutrient	Rate	Form
N	225 kg N/ha	Urea
P	40 kg P/ha	Triple super Phosphate
K	50 kg K/ha	Potassium-sulphate
Mg	40 kg Mg/ha	Magnesium-sulphate
S	44 kg S/ha	Degra-Sul; 0-0-0-90
Cu	10 kg Cu/ha	Copper-sulphate
Zn	20 kg Zn/ha	Zinc-sulphate
Fe	25 kg Fe/ha	[Na(Fe(EDTA)3H$_2$O)]
B	2.0 kg B/ha	Solubor; 20.5% B

Table 16. Fertilizer treatments applied in each installation

Installation	Treatments Applied			
	1	2	3	4
2	Control	N+S+B		
4	Control	Nitrogen	N+S+Mg+B	
5	Control	Nitrogen	N+S+Mg	
6	Control	Nitrogen	N+S+Mg	
7	Control	Nitrogen	Sulphur	N+S
13	Control	Nitrogen	N+S+B	
15	Control	Nitrogen	N+S	
16	Control	Nitrogen	N+S+B	
18	Control	Nitrogen	N+S+B	
21	Control	Nitrogen		
23	Control	Nitrogen	N+S	
24	Control	Nitrogen	N+S	
26	Control	Nitrogen	N+K+S	
28	Control	Nitrogen	N+K+S+B	
37	Control	Nitrogen	N+S	
38	Control	Nitrogen	N+S	N/2+S/2
39	Control	N+S		
41	Control	Nitrogen	N+S+Fe+Cu	
43	Control	Nitrogen	N+S	
48	Control	Nitrogen	N+S+B	
51	Control	Nitrogen	N+S+B	
54	Control	Nitrogen	N+S	
57	Control	Nitrogen	N+S+B	
58	Control	Nitrogen	N+S	
59	Control	Nitrogen	N+S+Mg+Cu+Zn+B	
61	Control	Nitrogen	N+S	N+S+Cu
102	Control	Nitrogen	N+K+S+Mg+B	
103	Control	Nitrogen	N+K+S+Mg+B	
104	Control	Nitrogen	N+S	
108	Control	Nitrogen	N+S	
109	Control	Nitrogen	N+K+S+Mg	
110	Control	Nitrogen	N+K+S+Mg+Zn	
111	Control	Nitrogen	N+K+S+Mg	
112	Control	Nitrogen	N+K+S	
113	Control	Nitrogen	N+K+S	
114	Control	Nitrogen	N+Cu	
115	Control	Nitrogen	N+S	
116	Control	Nitrogen	N+S+Mg	
117	Control	Nitrogen	N+P+S	
118	Control	Nitrogen	N+S	
120	Control	Nitrogen	N+K+S	
122	Control	Nitrogen	N+K+S	
125	Control	Nitrogen	N+S	
126	Control	Nitrogen	N+K+S	
127	Control	Nitrogen	N+K+S+Mg	
129	Control	Nitrogen	N+S+Mg	
132	Control	Nitrogen	N+K+S+Cu	
133	Control	Nitrogen	N+K+S	
134	Control	Nitrogen	N+S	
138	Control	Nitrogen	N+P+S+Mg	
139	Control	Nitrogen	N+P+S+Mg	
140	Control	Nitrogen	N+P+K+S+Cu	
141	Control	Nitrogen	N+P+K+S+Mg	
143	Control	Nitrogen	N+P+K+S+Mg	
144	Control	Nitrogen	N+S+Mg	
145	Control	Nitrogen	N+S+Mg	

» EVALUATION OF SITE-SPECIFIC GROWTH RESPONSE

» Stand and Site Variables

The previous sections have identified a large number of qualitative and quantitative variables describing site and fertilized stand characteristics. These variables, in combination with site classification, will be used to identify and test relationships between site and stand characteristics, nutrient deficiencies, and response to fertilizer treatments. A synopsis of site and stand variables available for analysis is given in Table 17. These variables will be used as independent variables in later analyses of growth response-site-stand interactions.

» Analysis of Growth Response

Response to fertilization will be measured at the end of the first, third, and, possibly sixth growing seasons. First year growth response will be examined through graphical analysis and pre- and post- treatment shoot-length ratios. In graphical analysis, the foliar concentration of the nutrient in question is plotted on the y-axis and the nutrients absolute content on the x-axis, a series of diagonal lines from the origin represent unit increases in needle weight. Given data from controls and treatment plots the direction and magnitude of resulting changes in all three parameters can be described by a single vector allowing interpretations to be made regarding response to treatment (Timmer and Stone 1978; Weetman and Fournier 1984).

Table 17. Variables available for quantification of site and stand characteristics.

Ecological variables:
- biogeoclimatic unit
- site unit
- actual SMR and SNR
- frequency of indicator species groups

Stand variables:
- stocking (stems/ha)
- site index (based on a minimum of 20 dominant and codominant trees)
- height, age, and diameter at breast height of each treated tree
- distance to the nearest neighbouring dominant or codominant tree in each of four 90° quadrants
- length and width of the live crown
- leaf area index
- average foliar concentrations (N, P, K, Ca, Mg, S, SO_4-S, Cu, Zn, Fe, active-Fe, Mn, and B) for each

Site and soil variables:
- elevation
- aspect
- slope, slope position and slope shape
- soil depth, texture and coarse fragment content
- rooting depth
- forest floor thickness
- humus form type
- kind and thickness of A soil horizon
- parent material mineralogy
- available water storage capacity

Forest floor and mineral soil chemical properties:
- pH, C, N, mineralizable-N, available P, exchangeable Ca, Mg, K, and CEC, and available Ca, Mg, Na, K, and S — expressed as concentrations and, where applicable, on a kg/ha basis.

The pre- and post-treatment shoot-length ratio method (Ballard and Majid 1985) attempts to estimate the growth of fertilized trees had they not been fertilized, and to subtract this estimate from their measured post-treatment increment. Average response for several trees within a treatment is calculated as follows:

$$av(Rf) = av(A_f) - av[(B_f)\, av(A_u/B_u)] \qquad [3]$$

where A = increment during the post-fertilization period; B = increment during the pre-fertilization period; R = absolute magnitude of response; av = the average of all replicates; f = fertilized; and u = unfertilized.

Third year response will be examined through measurement of radial increment at 3.5 m and 11.0 m above ground for each of five years prior to treatment and three years post-treatment. The first sample height of 3.5 m was chosen as this has been shown to be the lowest height for reliable estimates of radial increment [e.g. stem butt swell and eccentricity have reached an asymtotic minimum (Carter and Scagel 1987)] while the upper sample height of 11.0 m represents the approximate top of the second saw log. This measure will be based on ring width measurements of four increment cores taken at each of the above sample heights.

- **Analysis of Variance and Covariance**

Variance of measured growth response variables within and among treatment and control plots will be analyzed using 2-way analysis of variance (ANOVA) and covariance analysis (COVAR). Covariates such as initial dbh (Auchmoody 1985), length and width of the live crown, and several competitive stress indices (i.e. Arney 1978), and other tree-specific variables will be used in an attempt to reduce some of the variability not directly associated with each trees' response to treatment and improve the precision of response estimates. The COVAR analyses will concentrate on identifying the magnitude of growth response to fertilization. Interactions between added nutrient elements will be assessed where possible. ANOVA will also be used to compare response between installations that have been placed in different strata created on the basis of similarities in vegetation, site, and stand characteristics. Strata initially tested will be as outlined previously (see Vegetation and Site Units). Further strata based on natural groupings of foliar and/or soil chemical properties and components of the water balance model will also be identified through the use of descriptive statistics, cluster analysis, and principal components analysis. The response of member installations within each strata will be compared to the response among strata. Each strata will then be examined to see if it can be used as a meaningful basis for the identification of potential nutrient deficient stands and prediction of treatment response.

- **Individual Tree Response**

This project will also employ an individual tree method in an attempt to identify variables which influence response to fertilization. Each tree will be paired with its' associated growth response measurements, site, stand and soil characteristics. Relationship(s) between growth response to fertilization and these site and stand properties will then be examined over the complete population of treatment and control trees. This allows growth response to be evaluated on a much larger sample with the advantages associated with more degrees of freedom. It also facilitates development of predictive models of growth response across a broad range of stand or site conditions. However, it is recognized that with a total of only 56 installations there will be difficulties in dealing with interactions between variables affecting stand response. Development of response estimates specific to a wide range of unique stand and site conditions will likely have to involve an intermediate level of generalization (i.e. less accurate predictions).

Multiple regression will be used to identify those variables most suitable for the prediction of growth response. Although effort will be concentrated on variables which lend themselves to relatively simple and inexpensive description or classification in the field, other variables, which require quantitative analysis, will also be examined. The error term associated with each regression equation will be examined closely to determine whether partitioning of the data set will allow greater precision for predictive estimates made for trees growing under the influence of different environmental conditions (e.g may have greater predictive precision and accuracy on dry sites than on wet sites).

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